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Statistical Analysis of the Seismic Vulnerability of Mid-South Building Structures

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STATISTICAL ASSESSMENT OF THE SEISMIC VULNERABILITY OF MID-SOUTH BUILDING STRUCTURES

by

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ABSTRACT

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A study of buildings in Shelby County, Tennessee and Tipton County, Tennessee was conducted using a sidewalk survey procedure developed by the Federal Emergency Management Agency (FEMA), known as a Rapid Visual Survey (RVS). Its purpose is to identify buildings that are potentially at risk to a seismic event. A database of these buildings was generated from the data gathered in the RVS procedure. A loss estimation program developed by FEMA, known as HAZUS-MH MR3, was used to perform a more detailed analysis on the structures utilizing user defined ground motion maps. A rank of the structures was developed based upon the RVS procedure and the HAZUS output.

FEMA developed HAZUS-MH MR3 which estimates structural and non-structural losses for a variety of hazards. In this study, three earthquake scenarios were analyzed: a magnitude 6.5 earthquake based upon site-specific ground motion maps, a magnitude 7.7 earthquake based upon site-specific ground motion maps, and a magnitude 7.7 earthquake based upon ground motion maps provided by the United States Geological Survey (USGS). All of these ground motion maps simulate a desired earthquake scenario to perform a loss estimate of the buildings; however, the site-specific, user-supplied maps have many more unique ground motion parameters than the USGS maps. HAZUS provides loss estimates by computing damage state probabilities for each building. One objective of this research is to develop a prioritization of the structures based upon building performance from the HAZUS loss estimate and the RVS procedure, which has a possible application to aid emergency planners in selecting suitable locations to be used as

mass population shelters in the case of a seismic event. The second objective of this research is to assess how well the RVS procedure performs in identifying structures which may be seismically at risk as compared to the HAZUS output by performing a statistical analysis and hypothesis testing on the data. The results of this objective can be utilized in determining if the RVS procedure is suitable for the seismic evaluation of structures or if a more detailed, site specific analysis should be performed using hazard software like HAZUS. The third objective is to investigate how the building type and the construction time period of structures affect the results of HAZUS and the RVS using a statistical analysis. The results of the third objective can help in determining which construction materials perform better in a seismic event, which can have structural design applications for regions of high seismicity. The last objective is to examine how the effects of site-specific ground motion maps compare with those provided by the USGS, in HAZUS loss estimates.

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1 INTRODUCTION

1.1 Introduction

Throughout human history, earthquakes have been devastating phenomena around the world. In the past 100 years the understanding of seismology has greatly improved, along with the understanding of structural seismic resistance design theory. This study focuses on several building structures in Shelby County and Tipton County Tennessee. Shelby and Tipton Counties are located to the Southeast of the New Madrid seismic zone. As historical records show, this area has the potential to produce great magnitude earthquakes. Large enough seismic events could render the city of Memphis and other nearby towns unable to function economically and cause harm or loss of life to the citizens. Rapid Visual Screening (RVS) is a procedure developed by the Applied Technology Council (ATC) under contract to the Federal Emergency Management Agency (FEMA) and presented in the *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook 2nd Edition (FEMA 154 2002).* The RVS procedure is employed to identify, catalog, and grade structures that are susceptible to damage from seismic events. Although this procedure is intended for building structures, there are some cases in which non-building structures are surveyed.

The results of the RVS procedure may be utilized to determine roughly how safe a building may be in the case of a seismic event. This procedure employs a sidewalk survey during which building attributes are recorded and a numerical score is assigned based upon these building details. Finally, the procedure yields a hazard score known as the “S score”. The S score is a summation of the basic structural hazard (BSH) score and performance modification factors. A building’s BSH score is assigned based upon its primary lateral-force-resisting system. The performance modification factors are assigned based upon the building's attributes; such as: height, age, vertical and horizontal shape, and soil type.

A recent similar study (Boling 2009) utilized this procedure for the evaluation of mass population shelters. These shelters were prioritized and the ones that were deemed to be safe to risk of life were selected as emergency shelters in the case of a seismic event. In the event of an extreme natural disaster, an adequate shelter system will be necessary for people whose place of residence has been deemed unsafe for entry. Although these studies are concerned with earthquake disasters, a shelter's adequacy is also applicable for other natural disasters.

While this study involves prioritization of mid-south buildings that could be utilized as mass population shelters; the main purpose of this study is to explore statistical trends among the data obtained from these buildings. From the statistical analysis, formal conclusions will be made about a structure's damage after a seismic event based upon such things as: building type, construction date, and site-specific ground motion parameters.

Some of the buildings involved in this study are divided into multiple structures in order to accurately assess the primary lateral-force-resisting system. A total of 242 buildings were analyzed in this study. Since some of these buildings are composed of multiple structural systems, a total of 301 structures were analyzed. A total of 104 structures were surveyed in Shelby County, Tennessee; 32 were surveyed in Tipton County, Tennessee; data for 96 structures on The University of Memphis campus (Mize 2006), and data for 69 shelter structures (Boling 2009) were re-analyzed. Information obtained from the

RVS procedure was entered into a database program known as the Inventory Collection and Survey Tool (InCAST) for each of the 301 structures. The FEMA-developed software package HAZUS-MH MR3 was used for the loss estimation. InCAST is a database program that maps the structures' data into HAZUS, which runs in conjunction with a geographical information system (GIS) program. HAZUS-MH MR3 contains disaster modules for earthquakes, hurricanes, tornados, landslides, tsunamis, wild fires, coastal and river floods. However, for this study, only the earthquake module is utilized. The earthquake module employs geographical information, epicenter details, economic and structural building details along with mathematical fragility curves in order to output probabilistic damage estimates. Although HAZUS-MH MR3 contains volumes of embedded data involving population demographics and infrastructure data; only user-supplied data is used for this study (FEMA 433 2004).

The probabilistic damage states that are output from HAZUS-MH MR3 are categorized as: none, slight, moderate, extensive, and complete. A prioritization and statistical analysis of the 301 structures is performed based upon structure type, construction time period, the S score, and HAZUS-MH MR3 output. The main purpose of this research is to determine any trends and relationships among the RVS procedure and the HAZUS-MH MR3 analysis. The objectives of this research are:

(1) Prioritize the 301 structures based upon the HAZUS-MH MR3 output and S score.

(2) Make a formal conclusion as to how well the RVS procedure performs in identifying structures which may be seismically at risk as compared to the HAZUS-MH MR3 output.

(3) Make formal statements about building type and construction time period as they affect the HAZUS-MH MR3 output and S score.

(4) Make a formal conclusion as to how site-specific ground motion maps compare with those provided by the USGS with respect to the HAZUS-MH MR3 output.

1.2 Literature Review

Several papers and theses were consulted while performing this study. The methodology of the RVS procedure and examples of how to calculate a building's S score are given in FEMA 154 (2002) and FEMA 155 (2002). *Assessment of the Seismic Vulnerability of the University of Memphis Main Campus Buildings* (Mize, 2006), and *Assessment of the Seismic Vulnerability of Shelby County Mass Emergency Shelters* (Boling, 2009) are two masters theses which utilized the RVS procedure and provided a basis for this research. HAZUS-MH MR3 (2006a, 2006b) and FEMA 433 (2004) provide details on the technical aspects of the software; and for this study, the earthquake module. A brief discussion of these sources is found below.

1.2.1 *FEMA 154 and FEMA 155*

Rapid Visual Screening of Buildings for Potential Seismic Hazards, FEMA 154 (2002) discusses the procedure and methodology of RVS of buildings. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation, FEMA 155* (2002) details the empirical relationship among building type, numerical scores, and performance modification factors which are utilized in the RVS procedure. The term "sidewalk survey" was coined due to the fact that the screener can identify most necessary building attributes by simply walking around the building and observing from the sidewalk. First, the screener must identify the main lateral-force-resisting system of the structure, as well as the material of construction (i.e. concrete, steel, timber). Once this is done, the screener must identify secondary features of the building and its location. These features include: specific location, height, floor area, soil type, and vertical and horizontal irregularities. The final S score is composed of the BSH score and appropriate performance modification scores either added or subtracted from the BSH. If a building receives an S score below a certain cut-off, the building is said to require a detailed seismic evaluation by a licensed engineer. A cut-off S score of 2.0 is suggested and appropriate for infrequent, but possible earthquake loadings, based upon present seismic design criteria (FEMA 154 2002). The cut-off S score of 2.0 is used in for this research (Boling 2009 and Mize 2006).

As with all procedures, the RVS method has its limitations. A limitation of this procedure is that the screener may be limited in what he or she can see from the sidewalk. It is possible that there are multiple structural systems within a building that cannot be observed from the sidewalk. It is more advantageous if the screener can gain access to the interior of the building to gather more insight. For buildings with multiple structures, multiple S scores should be calculated and the lowest score should control. Due to this practice, some buildings may be deemed as hazardous when they are actually not.

1.2.2 *Assessment of the Seismic Vulnerability of the University of Memphis Main Campus Buildings (Mize 2006)*

The purpose of this study was to generate economic, structural, and loss of life estimates for 96 structures on The University of Memphis main campus. Mize (2006) utilized the RVS method and constructed a building inventory database. HAZUS-MH

MR1 was used for the loss estimates. In addition, a summary was provided of S scores and corresponding HAZUS-MH MR1 output values.

1.2.3 *Assessment of the Seismic Vulnerability of Shelby County Mass Emergency Shelters (Boling 2009)*

Boling (2009) utilized the RVS procedure on 69 buildings in Shelby County that could potentially be used as mass population emergency shelters in the event of a natural disaster. The identification and assessment of shelters allows emergency managers to better understand the capacity and functionality of the shelter system. HAZUS-MH MR3 was used for the loss estimates. The result of this research was a prioritization of the shelter buildings using the S score and output values from HAZUS-MH MR3.

1.2.4 *HAZUS-MH MR3 (2006a and 2006b) and FEMA 433*

Three FEMA documents were consulted in order to further the understanding of the use of HAZUS-MH MR3. These documents include: *Using HAZUS-MH for Risk Assessment: FEMA 433* (2004), *HAZUS-MH MR3 Earthquake Model Technical Manual* (2006a), and *HAZUS-MH MR3 Earthquake Model User's Manual* (2006b). FEMA 433 (2004) provides details on all the HAZUS-MH MR3 modules, as well as in-depth system requirements and installation procedures. The *HAZUS-MH MR3 Earthquake Model Technical Manual* (2006a) and *HAZUS-MH MR3 Earthquake Model User's Manual* (2006b) documents provide detailed explanations of the earthquake module and technical specifications of the mathematics involved in the loss and damage estimations. The user's manual further explains how to prepare and define input data and how to interpret the output data.

2 METHODOLOGY

2.1 The Rapid Visual Survey (RVS) Procedure

FEMA 154 (2002) outlines the RVS procedure which is used to gather building data. This data is then used to develop the Advanced Engineering Building Module (AEBM) that is utilized by the HAZUS-MH MR3 software. The RVS procedure is best performed in a sequence of steps beginning with pre-field planning and site specific data gathering. In this stage, the screener should determine the level of seismicity of the desired region, be familiar with the local seismic code adoption dates, and obtain necessary soil information. FEMA 154 (2002) provides three data collection forms based on the seismicity of the desired region: high, moderate, and low. After determining the seismicity of the region, the screener performs the sidewalk survey at desired locations, recording the building type (i.e. the main lateral-load-resisting system) and any vertical or horizontal irregularities. The screener should make sketches or take photographs of the buildings being surveyed in order to make future references. At a minimum, one photograph is required of each building. However, several photographs of each building from different angles can provide additional reference data later. For this study, at least three photographs were taken of each building visited. A good approximation of the total usable floor area should also be noted. All of this information is recorded on the RVS data collection form for each individual building. If a building is determined to have more than one type of structural system, data should be recorded for each system. Gaining access to building plans, construction materials, or other building data may be helpful. Tools that should accompany the screener include: pencil, clipboard with extra data collection forms, a copy of the FEMA 154 (2002) handbook, map of the area being surveyed, and a camera.

2.1.1 Shelby County and Tipton County, Tennessee

Shelby County and Tipton County, Tennessee were selected as the study area for this research. This area is in close proximity to the New Madrid seismic zone which raises the probability that the area will experience seismic events. Figure 2-1 shows the location of Shelby County and Tipton County in Tennessee. The statistical analyses that were performed on structures in this research aids in the further understanding of the behavior of certain building types in the study region which may come under the influence of seismic activity. Most of the structures in this study have been deemed as possible mass population shelters in the event of a natural disaster. The results of this study may be used to aid emergency managers to locate acceptable buildings in this area in case of any natural disaster.

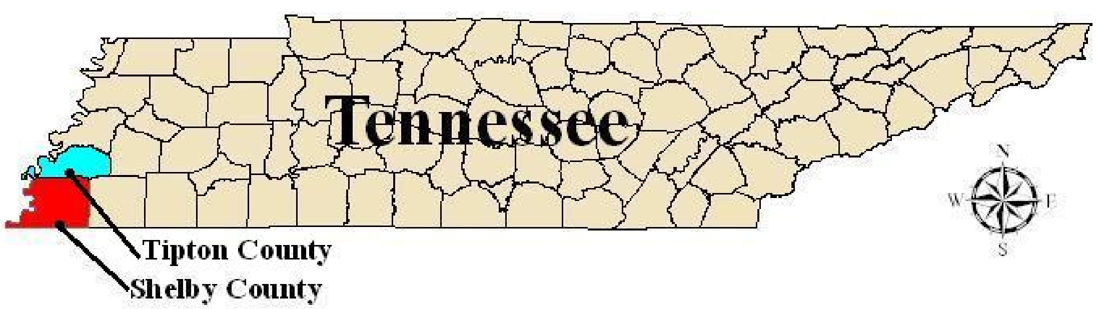


Figure 2-1. Location of Shelby County and Tipton County

The buildings in this study were assessed using the RVS procedure. The results, along with HAZUS-MH MR3 output probabilistic damage states, and statistical analyses were maintained in a Microsoft Excel database. In order to protect the identity of the buildings and businesses involved in this study, building and business names were omitted. Digital photographs were taken and aerial photographs from Google Earth were documented for each structure for any post-field observations that may occur.

2.1.2 Determining the Seismicity Region of a Study Area

There are two common ways to easily determine the seismicity of a region. The first way is to locate the study area on Figure 1-1 in FEMA 154 (2002) and report the corresponding seismicity. Figure 2-2 depicts Figure 1-1 of the FEMA 154 (2002) document.

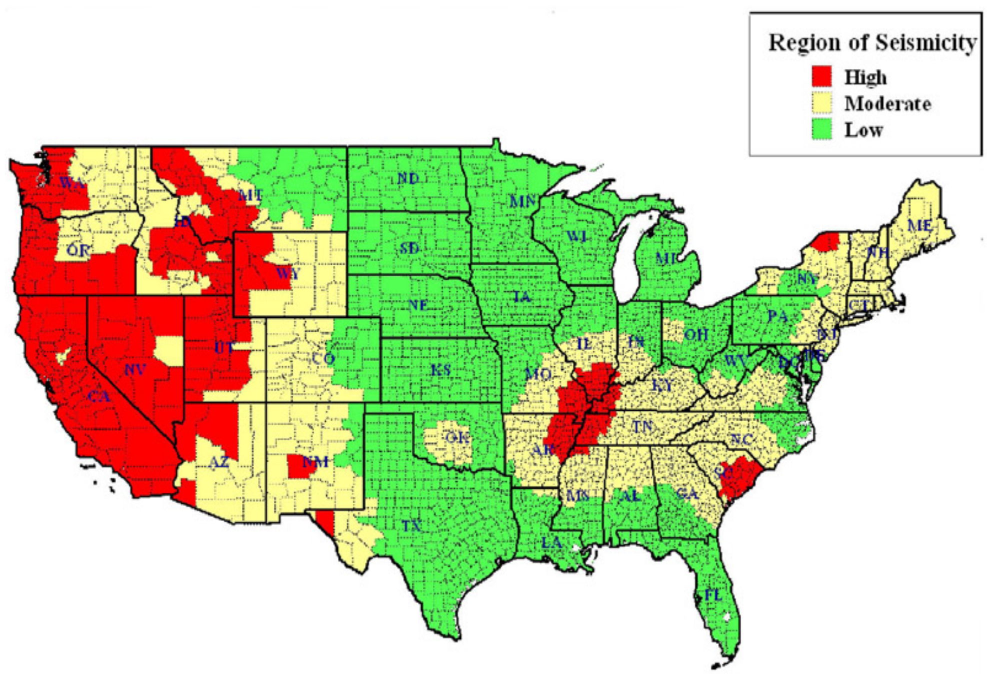


Figure 2-2. Seismicity Regions, Figure 1-1 of FEMA 154 (2002)

The second method of determining a seismicity of a study area is to utilize the United States Geological Survey (USGS) web site. Locate the 2008 United States National Seismic Hazard Maps link and use a 2% probability of exceedance in 50 years. Obtain the 0.2 sec Spectral Acceleration (0.2 sec SA) and 1.0 sec Spectral Acceleration (0.2 sec SA) values. These two values should each be multiplied by 2/3 and then compared to the corresponding values associated with each seismicity region shown in Table 2-1 of FEMA 154 (2002). Table 2-1 depicts Table 2-1 of the FEMA 154 (2002) document.

Table 2-1. Seismicity Regions, Table 2-1 of FEMA 154 (2002)

Regions of Seismicity with Corresponding Spectral Acceleration Response (from FEMA 130)		
Region of Seismicity	Spectral Acceleration Response, SA (short-period, or 0.2 sec)	Spectral Acceleration Response, SA (long-period, or 1.0 sec)
Low	less than 0.167 g (in horizontal direction)	Less than 0.067 g (in horizontal direction)
Moderate	greater than or equal to 0.167 g but less than 0.500 g (in horizontal direction)	greater than or equal to 0.067 but less than 0.200 g (in horizontal direction)
High	greater than or equal to 0.500 g (in horizontal direction)	greater than or equal to 0.200 g (in horizontal direction)
Notes: g = acceleration of gravity		

For this study, both methods were utilized. From Figure 2-1, it was determined that the seismicity region of interest is High. From the USGS seismic hazard interactive map, a latitude value of 35.38° N and a longitude value of 89.82° W were selected and entered into the map. These values were chosen since this location is near the center of the Shelby County and Tipton County Border and that is the region with which this project is concerned. The corresponding ground motion values were returned:

0.2 sec SA = 1.500 g

1.0 sec SA = 0.437 g

Multiplying each value by 2/3 yields,

(2/3) x (1.500 g) = 1.000 g

(2/3) x (0.437 g) = 0.291 g

Comparing these values with the corresponding values listed in Table 2-1 concurs that the area of study is indeed a High seismicity region. To be more formal, the second method should be performed on each structure being analyzed. However, from Figure 2-2, it is seen that all of Shelby County and Tipton County fall within the high seismicity region. Figure 2-3 shows the High seismicity RVS data collection form.

Rapid Visual Screening of Buildings for Potential Seismic Hazards

FEMA-154 Data Collection Form

HIGH Seismicity

Scale:

Address: ______________________________

______________________ **Zip** __________

Other Identifiers ______________________________

No. Stories ____________________ **Year Built** ______

Screener ____________________ **Date** __________

Total Floor Area (sq. ft.) ______________________________

Building Name ______________________________

Use ______________________________

PHOTOGRAPH

OCCUPANCY					SOIL TYPE						FALLING HAZARDS			
Assembly	Govt.	Office	Number of Persons		A	B	C	D	E	F	☐	☐	☐	☐
Commercial	Historic	Residential	0 – 10	11 – 100	Hard Rock	Avg. Rock	Dense Soil	Stiff Soil	Soft Soil	Poor Soil	Unreinforced Chimneys	Parapets	Cladding	Other: ______
Emer. Services	Industrial	School	101-1000	1000+										

BASIC SCORE, MODIFIERS, AND FINAL SCORE, *S*

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	**4.4**	**3.8**	**2.8**	**3.0**	**3.2**	**2.8**	**2.0**	**2.5**	**2.8**	**1.6**	**2.6**	**2.4**	**2.8**	**2.8**	**1.8**
Mid Rise (4 to 7 stories)	N/A	N/A	+0.2	+0.4	N/A	+0.4	+0.4	+0.4	+0.4	+0.2	N/A	+0.2	+0.4	+0.4	0.0
High Rise (> 7 stories)	N/A	N/A	+0.6	+0.8	N/A	+0.8	+0.8	+0.6	+0.8	+0.3	N/A	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-2.5	-2.0	-1.0	-1.5	N/A	-1.0	-1.0	-1.5	-1.0	-1.0	N/A	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-1.0	-1.0	-0.8	-0.6	-0.8	-0.2	-1.2	-1.0	-0.2	-0.8	-0.8	-1.0	-0.8	-0.2
Post-Benchmark	+2.4	+2.4	+1.4	+1.4	N/A	+1.6	N/A	+1.4	+2.4	N/A	+2.4	N/A	+2.8	+2.6	N/A
Soil Type C	0.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Soil Type D	0.0	-0.8	-0.6	-0.6	-0.6	-0.6	-0.4	-0.6	-0.6	-0.4	-0.6	-0.6	-0.6	-0.6	-0.6
Soil Type E	0.0	-0.8	-1.2	-1.2	-1.0	-1.2	-0.8	-1.2	-0.8	-0.8	-0.4	-1.2	-0.4	-0.6	-0.8

FINAL SCORE, *S*

COMMENTS

Detailed Evaluation Required

YES NO

* = Estimated, subjective, or unreliable data
DNK = Do Not Know

BR = Braced frame
FD = Flexible diaphragm
LM = Light metal

MRF = Moment-resisting frame
RC = Reinforced concrete
RD = Rigid diaphragm

SW = Shear wall
TU = Tilt up
URM INF = Unreinforced masonry infill

Figure 2-3. High Seismicity RVS Data Collection Form

2.1.3 The Benchmark Year

The benchmark year is defined by FEMA 154 (2002) as the year in which significant improvement in seismic codes were adopted and enforced for a region. This is connected to the performance modifier on the RVS data collection form that determines if a building is "Pre-Code" or "Post-Benchmark" constructed. Based upon the research of Mize (2006) and Boling (2009), the benchmark year for Shelby and Tipton Counties was determined to be 1991.

2.1.4 Calculating the S Score

The RVS procedure concludes with the calculation of the S score, which allows the screener to categorize a building as either "in need for a detailed investigation by a trained seismic structural engineer" or "safe to risk of life" (FEMA 154 2002). In order to distinguish between these two categories, a cut-off score must be specified. FEMA 155 (2002) defines a cut-off score of S = 2.0 as being equal to the probability of 1 in 100 buildings having "major damage", a score of S = 3 corresponds to the probability of 1 in 1000 buildings having "major damage", and so on. FEMA 154 (2002) recommends the cut-off score of S = 2.0 and it was used in this study. Therefore, buildings with a cut-off score lower than 2.0 are deemed unsafe for immediate occupancy after a seismic event and should be further evaluated by a licensed engineer.

A structure's S score is derived based on the probability that the structure will experience major damage during a seismic event. Let "P(major damage)" be defined as the probability of major damage to a building. For S = 1, $P(\text{major damage}) = \frac{1}{10^1}$. For S = 2,

$P(\text{major damage}) = \frac{1}{10^2}$ (FEMA 155 2002). Continuing by induction, the following formula is proposed:

$$P(\text{major damage}) = \frac{1}{10^S} \tag{2.1}$$

Taking the logarithm, base 10 of each side of Equation (2.1) and simplifying, gives:

$$S = -\log_{10}[P(\text{major damage})] \tag{2.2}$$

Table C1 of Appendix F in FEMA 155 (2002) shows a numerical example, utilizing Equations (2.1) and (2.2). Table 2-2 depicts Table C1 of Appendix F in FEMA 155 (2002).

Table 2-2. Numerical Example Using S Score, Table C1 of FEMA 155 (2002)

Type	***No. Buildings***	***S***	***P (Major Damage)***	***Expected No. Bldgs. With Major Damage***
Wood	3,000	4.5	1/31,600	Approx. 0
Tilt-Up	100	2.0	1/100	Approx. 1
URM	100	1.0	1/10	Approx. 10
Br. Steel Fr.	100	3.0	1/1,000	Approx. 0

The “Expected No. of Bldgs. With Major Damage” column is calculated by multiplying the number of buildings by their respective “probability of major damage” value.

Information that does not affect the S score includes: total floor area, building name, occupancy data, and presence of falling hazards. Data that does affect the S score includes: building type, building height, building shape, year built (pre-code or post-benchmark), and soil type. The BHS score of a building is determined by identifying the building type which defines the primary lateral-force-resisting system. This can be done prior to going to the field if there is access to building plans. Otherwise, this may be determined during the sidewalk survey. If the building type is difficult to discern due to hiding of structural elements within cladding, the screener should examine window spacing and apparent construction materials. If it is still difficult to determine the building type, the screener should eliminate obvious choices and note all possible structural types for the building and calculate an S score for each possibility. The lowest S score should control. Next, appropriate score modifiers are identified. Table 2-3 lists the model building types that are identified on the RVS data collection form. These building types are consistent with the building structure types used in the HAZUS-MH MR3 software. A detailed definition of building types from the HAZUS-MH MR3 Technical Manual is presented in Appendix A.

Table 2-3. Building Types Identified on the RVS Data Collection Form

Structure Type	Description
W1	Light wood-frame residential and commercial buildings < 5,000 ft^2
W2	Light wood-frame buildings > 5,000 ft^2
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frame buildings with cast-in-place concrete shear walls
S5	Steel frame buildings with unreinforced masonry infill walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear-wall buildings
C3	Concrete frame buildings with unreinforced masonry shear walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM1	Reinforced masonry buildings with flexible floor and roof diaphragms
RM2	Reinforced masonry buildings with rigid floor and roof diaphragms
URM	Unreinforced masonry bearing-wall buildings

Score modifiers are numerical values assigned based upon building height (mid rise or high rise), plan irregularities, vertical irregularities, year built, and soil type. A building is said to be a mid rise building if it has 4 to 7 stories. A high rise building has more than 8 stories. A building with a plan irregularity (horizontal irregularity) is one in which re-entrant corners exist or that is E, L, T, U, or + shaped. A score modifier is assigned for plan irregularities since this could cause internal torsion within the structure. Vertical irregularities are defined as buildings with setbacks, hillside buildings, and buildings with soft stories. A soft story is a story of a building in which there are large gaps between structural supports. An example of this is an office building with a parking garage on the bottom floor. The year a building was constructed is important in determining if the building was built before the benchmark year. The soil type of a region may be determined from previous studies of the area or soil type maps. Soil Type D is the accepted type for this study region. FEMA 450-1 (2003) defines a type D soil as a stiff soil with a shear wave velocity, v_s, between 600 ft/sec and 1,200 ft/sec, or, with either Standard Penetration Test (SPT) blow counts, N, between or equal to 15 and 50 or undrained shear strength, s_u, between 1,000 psf and 2,000 psf.

2.2 HAZUS-MH MR3

HAZUS-MH MR3 is a sophisticated hazard analysis program that has the ability to analyze a region for several different types of hazards. HAZUS-MH MR3 may also be customized by the user to accommodate different levels of accuracy. The analysis is classified as a Level 1, 2, or 3. A Level 1 analysis is the most basic analysis and uses default hazard inventory data with minimal or no user supplied data. This level of analysis is a good way to get a general idea of risk mitigation for a region; however, it contains high levels of uncertainty. A Level 2 analysis requires that the user supply hazard data for the desired region rather than accepting default values. Using the local data, the loss estimate is refined and produces much more accurate results compared to a Level 1 analysis. A Level 3 analysis requires the same information as a Level 2 analysis, and in addition, involves augmenting the programs loss estimation models. A Level 3 analysis is intended to be performed by expert users of the software.

2.2.1 Level 2 Analysis: Shelby County and Tipton County, Tennessee

For this study, a Level 2 analysis was performed. Instead of relying on national databases and embedded data, the building input data was collected and recorded using the database program InCAST. All of the structures within Shelby County and Tipton County were analyzed using two different types of ground motion maps. The first set of maps used was generated from the local data by Dr. Chris Cramer of the Center for Earthquake Research and Information (CERI) at the University of Memphis in Memphis, Tennessee. The second set of maps used was the set available from the United States Geological Survey (USGS) website. The USGS maps are less detailed than those developed by Cramer since they only provide a few distinct ground motion values for all of Shelby County and Tipton County. Cramer's maps are more detailed and account for several hundred distinct ground motion values for the study region (Cramer 2004). The maps generated by Cramer are the most up-to-date representation of expected ground motions for this region of the country.

For this study, two independent earthquake scenarios were studied using Cramer's maps and one scenario was explored using the USGS maps. The scenarios were a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone (Cottonwood Grove Fault) using Cramer's data and the USGS data and a magnitude 6.5 earthquake on the southern end of the southwest arm at Marked Tree, Arkansas using only Cramer's data. Each scenario required ground motion maps for 0.3 second spectral acceleration, 1.0 second spectral acceleration, peak ground acceleration, and peak ground velocity. Boling (2009) explored the development of the maps using Cramer's data in GIS and converting them into a HAZUS-MH MR3 compatible format. A procedure for developing HAZUS-MH MR3 compatible ground motion maps is provided in Appendix B. This is the same procedure that was used and referenced by Boling (2009). Appendix C contains a visual representation of all of the ground motion maps generated by Cramer and the USGS.

2.2.2 Advanced Engineering Building Module (AEBM)

The AEBM is a tool that facilitates the implementation of building specific loss estimation within HAZUS-MH MR3. The AEBM procedure utilizes the HAZUS-MH MR3 loss estimation methods along with nonlinear static analysis. A Level 3 analysis allows the user to modify the pre-defined fragility curves within HAZUS-MH MR3. For the Level 2 analysis performed in this study, the default fragility curves and damage functions for 36 generic building types were utilized without modification. Site data on soil type (and ground failure) cannot be input directly to the AEBM, but can be input to the HAZUS software as soil or ground failure data maps or by modifying default data on a census tract-by-census basis. If the user provides no information, the AEBM will calculate damage and loss based on ground shaking corresponding to the default soil type (i.e, Soil Class D) and will ignore the effects of ground failure (HAZUS-MH MR1 2003). Damage and loss functions for these generic model building types are considered to be reliable predictors of earthquake damage; however, they may not be good indicators of damage for individual buildings (HAZUS-MH MR3 2006).

To utilize AEBM, a building inventory must be assembled containing specific data for each structure analyzed. This data includes: building location, occupancy class, replacement value and financial data, and building size (HAZUS-MH MR3 2006). HAZUS-MH MR3 default data may be relied on for the analysis if there is unknown information for some data fields such as general occupancy data, population demographics, and economic parameters. After the building inventory has been established, building profiles must be created for each individual structure. The profiles are composed of: profile name, occupancy class, building type, and seismic design level. The seismic design level is determined from the age of the building (pre- or post-benchmark). The profile assigned to each structure matches the appropriate fragility curve and capacity function to the structures.

2.2.3 Fragility Curves

A fragility curve describes the probability of being in a specific damage state as a function of the size of earthquake input (HAZUS-MH MR3 2006b). Structural fragility curves model the structural behavior of the building when subject to ground shaking. For structural damage, the fragility curves express damage as a function of building displacement (HAZUS-MH MR3 2006b). Damage state envelopes are developed from the amount of lateral displacement the structure experiences as well as the damage state probability; where the horizontal axis of the curve is the lateral building displacement and the vertical axis is the damage state probability. Although it is possible to modify the default fragility curves within HAZUS, it is not recommended unless it is done by an engineer who is an expert in this line of research. Figure 2-4 depicts Figure 9.19, a generic building fragility curve, of the HAZUS-MH MR3 *Earthquake Model User's Manual* (2006b).

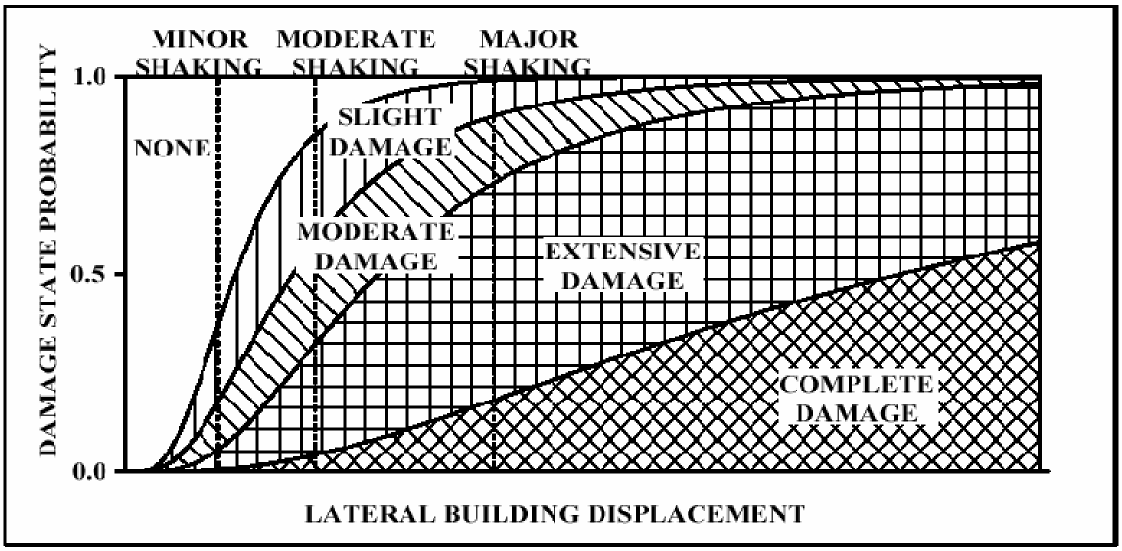


Figure 2-4. Sample Building Fragility Curve, Figure 9.19 of HAZUS-MH MR3 *Earth quake Model User's Manual* 2006b

2.3 Statistical Analysis

An Immediate Occupancy (IO) factor is calculated as the summation of the "none" and "slight" damage states. This is the probability of immediate occupancy after a seismic event (Boling, 2009). The *P*(major damage) of each structure was calculated as the summation of "extensive" and "complete" damage states. A HAZUS based-S score (S_H score) was calculated from the *P*(major damage) using Equation (2.2). All damage states are combined to compute a Building Replacement Cost (*BRC*). The *BRC* factor represents the percentage of the building's value that will need to be provided for repair (Boling 2009). One objective of this research was to perform a statistical analysis on the 301 structure data set and make formal conclusions about the relationships among the

BRC factor, IO factor, S score, and S_H score. The first data organization and analysis that was performed involved the structural and physical features of each of the structures. The raw data gathered was tabulated and categorized by building type, occupancy class, construction date, horizontal and vertical shape qualities, and building height to easily observe the number of structures of each category. The second statistical analysis performed used the output from HAZUS-MH MR3.

2.3.1 HAZUS-MH MR3 Output

The output of HAZUS-MH MR3 is a set of damage state probabilities for each of the 301 structures. The damage states are classified as: none, slight, moderate, extensive, and complete. These five damage state probabilities are computed for three performance groups: structural, drift sensitive non-structural, and acceleration sensitive non-structural. Therefore, fifteen values are estimated from HAZUS-MH MR3 for each of the 301 structures. The *BRC* factor, IO factor, and S_H score were calculated using these damage state probabilities. The *BRC* factor is defined as:

$$BRC = \sum_{i=1}^{3} BRC_i \tag{2.1}$$

$$BRC_i = \sum_{j=1}^{4} RCR_{jk} * P_{ij} \tag{2.2}$$

where BRC_i = the Building Replacement Cost percentage for performance groups i (SS, NSD, and NSA);

RCR_{jk} = the Repair Cost Ratio for damage states j (slight, moderate, expensive, complete) as a function of occupancy class *k* (*k* = 1 to 32) as found in HAZUS-MH MR3 Earthquake Model Technical Manual, see Appendix F;

P_{ij} = the HAZUS-MH damage state probabilities for performance group *i* and damage state *j*;

The first analysis performed on the *BRC* factor, IO factor, and S score was a prioritization of the structures based upon the *BRC* factor from smallest to largest, then IO factor from largest to smallest, and then the S score from largest to smallest. A master rank was assigned to each structure based upon this ordering. Plots were then generated, for each earthquake scenario, to observe any trends and relationships between the *BRC* factor, IO factor, S score, and master rank for all structures. For mass-shelter application purposes, the structures were divided into five categories based upon the *BRC* factor. These five categories divide the structures in *BRC* ranges of 0 - 2%, 2 - 5%, 5 - 25%, 25 - 50%, and 50 - 100%. A point coverage was created in ArcGIS and overlaid on a population density map of Shelby County and Tipton County. From this map, one can observe where acceptable and poor performing structures are located with respect to population density. Maps such as this could allow emergency planners to locate the acceptable performing structures and potentially use them as shelters in the case of an earthquake or other natural disaster.

2.3.2 Analysis of Variance (ANOVA)

A Single Factor Analysis of Variance (ANOVA) is a type of hypothesis test which allows one to make comparisons of means between multiple samples as specified levels of significance. This type of test allows users to determine whether or not differences observed between sample means are statistically significant, or if they are due to variation within the samples themselves. The "single factor" being considered for this research is the *BRC* factor. In order to compare the site-specific ground motion maps to the USGS ground motion maps the ANOVA test was performed on the *BRC* factors generated from Cramer's magnitude 7.7 data and the USGS magnitude 7.7 data. The set of *BRC* factors from Cramer's data was taken as one population group and the set from the USGS data was taken as another population group. Since the logic underlying a hypothesis test is that of a proof by contradiction, the assumed statement about the two population groups was that their means are equal at some level of significance. Although the choice of the level of significance is somewhat arbitrary, in practice, $\alpha = 0.05$ is commonly used. The selected level of significance for this research was taken to be 95%. Therefore, the null hypothesis (H_o) of the ANOVA test states that there is no statistically significant difference between the mean *BRC* factor based on Cramer's ground motion data and the mean *BRC* factor based on the USGS ground motion data in Shelby County and Tipton County for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone. The alternative hypothesis (H_a) to which the null hypothesis is compared states that there is a statistically significant difference between the mean *BRC* factor based upon the Cramer ground motion data and the mean *BRC* factor based on the USGS ground motion data in Shelby County and Tipton County for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone. Since for this particular hypothesis test, there are only two data sets; the alternative hypothesis states that the two means are different. There are several formulae that are used for an ANOVA test. These formulae ultimately lead to the calculation of the test statistic of the sample. First, the sum of the squared deviations (*TSS*) is computed as:

$$TSS = \sum_i \sum_j y_{ij} - \frac{G^2}{n} \tag{2.3}$$

where y_{ij} is the j^{th} observation from population i, n is the total sample size, and G is the grand sum of all observations from all populations. Next, the sum of the squares between samples (SSB) and the sum of the squares within samples (SSW) are computed. These factors are a measure of the variation of the means between and within samples, respectively.

$$SSB = \sum_i \frac{T_i^2}{n_i} - \frac{G^2}{n} \tag{2.4}$$

$$SSW = TSS - SSB \tag{2.5}$$

The values of T_i and n_i are the sum of the sample observations from population i and number of observations from population i, respectively. From the SSB and SSW, the mean square between samples (s_B^2) and mean square within samples (s_W^2) can be calculated.

$$s_B^2 = \frac{SSB}{t - 1} \tag{2.6}$$

$$s_W^2 = \frac{SSW}{n - t} \tag{2.7}$$

The parameter t represents the number of populations. If the mean square between samples value is large, this indicates that there is a significant difference in the means of the samples being analyzed. If the mean square within samples value is large, this indicates that there is more variation among the data points within a particular sample. The parameter t represents the number of populations. Finally, F_{calc} is the ratio of the mean square between samples to the mean square within samples.

$$F_{calc} = \frac{s_B^2}{s_W^2} \tag{2.8}$$

F_{table} is the tabular value that corresponds to the level of certainty assumed for the test. This is based upon the one-tailed F-distribution. The F-value is represented as the x-axis on the F-distribution graph. The null hypothesis is rejected if $F_{calc} > F_{table}$. Another output of many statistics package programs is the actual p-value. This is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, when assuming the null hypothesis is true. A tabular summary of a typical ANOVA is given in Table 2-4, where *SS* is the sum of the squares, *df* is the degrees of freedom based upon total sample size and number of populations, MS is the mean square value, F is the F_{calc} value, and F_{crit} is the F_{table} value.

Table 2-4. Single Factor ANOVA Output Table

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	F_{crit}
Between Groups	*SSB*	t - 1	$s_B^2 = \frac{SSB}{t - 1}$	$\frac{s_B^2}{s_W^2}$	*p-value*	F_{table}
Within Groups	*SSW*	$n - t$	$s_W^2 = \frac{SSW}{n - t}$			
Total	*TSS*	n - 1				

An ANOVA test was performed on each of the *BRC* factor data sets, IO factor data sets, S score and S_H score data sets generated for the three earthquake scenarios, individually, based upon building type and construction time period. The results should help determine how the building type and construction time period affected the *BRC* factor, IO factor, S score, and S_H score. To eliminate all negative S score and S_H score values, as negative values skew the mean and variances, the S scores and S_H scores were scaled by adding a value of 10. For the scaled scores, the cut-off S score and S_H score becomes 12 instead of 2. The building type and construction date time period criteria were chosen because they are the two main data fields that are mapped into HAZUS for the seismic analysis and they have the largest impact on the S score. Because there are several building types that contain only a few data points, the building types which are of the same basic construction material were combined. The building type categories based upon construction material are: concrete (C1, C2, C3), pre-cast concrete (PC1, PC2), reinforced masonry (RM1, RM2), steel (S1, S2, S3, S4, S5), unreinforced masonry (URM), and wood (W1, W2). The construction date time periods were divided into the following intervals: Pre-1931, 1931-1950, 1951-1970, 1971-1990, and 1991-2010. Plots were generated for each of the building type categories and the construction date time periods, for all three earthquake scenarios, to compare the scaled S score with the scaled S_H score. It should be noted that scaling all of the S scores does not change the comparable trends.

2.3.3 Tukey's Multiple-Comparison Procedure

The Single Factor ANOVA tests performed in this research are an excellent method to show that the means of the population groups are either identical or to show that at least one of them is different from the others. The practical application for this research can show that statistically, there is or is not a significant difference in the mean *BRC* factors, IO factors, S scores, and S_H scores for a collection of population groups (ie. Cramer's data vs. USGS data, construction date, and construction material). However, these ANOVA tests can not directly determine which sample means are statistically significantly different from one another. In order to determine which categories are significantly different from the others, a statistical follow up test is performed. Tukey's multiple-comparison procedure, named after John Tukey, was chosen for this study for its relative simplicity and broad scope of problems it covers. The main disadvantage of Tukey's multiple-comparison procedure is its weak power, that is, it has a low sensitivity to small location differences. Tukey's multiple-comparison test was performed for the three earthquake scenarios on construction date and construction material.

In order to concisely present the results from Tukey's method, the analysis was performed in several intermediate steps and tabulated. First, the *BRC* factors, IO factors, scaled S scores, and scaled S_H scores were ordered based upon the construction date time periods and building type categories. When the null hypotheses from the ANOVA tests were rejected, Tukey's method was implemented utilizing the following expression,

$$\frac{q(\alpha,k,v)}{\sqrt{2}}\sqrt{MS_{Error}}\sqrt{\frac{1}{n_r}+\frac{1}{n_s}} \tag{2.9}$$

where, $q(\alpha,k,v)$ is the upper 100α percentage point of the *Studentized range* distribution and α is the level of significance for comparing k means with $v = N - k$ degrees of freedom. N is the total number of data points, for the mean square error (MS_{Error}). The parameters n_r and n_s are the number of data points in the two populations being compared.

Tables for the *BRC* factor, IO factor, scaled S score, and scaled S_H score were formed to organize the data from Tukey's method, and a pair wise comparison was made based upon the ascending order of the means of the construction date time periods and building type categories. Table 2-5 shows an example of these tables.

Table 2-5. Tukey Multiple Comparison Table

Groups	*Average*	*Counter*	*Comparison*	*Difference*		*Rejection Region*
Group 1	Ave. 1	1	n vs (n-1)	(Ave. n) - (Ave. n-1)	> or <	Expression (2.9)
Group 2	Ave. 2	2	·	·	·	·
·	·	·	·	·	·	·
·	·	·	·	·	·	·
·	·	·	·	·	·	·
Group n-1	Ave. n-1	n-1	·	·	·	·
Group n	Ave. n	n	·	·	·	·
			2 vs 1	Ave. 2 - Ave. 1	·	·

The *Groups* column is the list of construction date time periods or building type categories given in ascending order of the *Average* column. The *Average* column contains either the mean *BRC* factor, IO factor, scaled S score, or scaled S_H score in ascending order. Placing the means in ascending order allows for the comparisons to be made without the direct use of confidence intervals. The *Counter* column is for labeling purposes so the *Comparison* column can be easily followed. The *Comparison* column compares each of the groups one by one, starting with the groups with the highest means. The *Difference* column is the difference between the means of the two counters being compared one by one. This is analogous to the F_{calc} value in a standard ANOVA table. The *Rejection Region* column is analogous to the F_{table} value in a standard ANOVA table. The values in the *Rejection Region* column are calculated using Expression (2.9). If a value in the *Dif-*

ference column is larger than its corresponding value in the *Rejection Region* column, then it is said that those two counters (groups) are significantly different from each other (ie. $F_{calc} > F_{table}$). For this research, this multiple comparison shows which pairs of groups are significantly different from one another by comparing all of the combinations of the groups (construction date time periods or building type categories) one by one.

3 RESULTS

3.1 RVS Results

During this study, the RVS procedure was applied to 73 buildings in Shelby County and 20 buildings in Tipton County. In a previous study done by Mize (2006), the RVS procedure was performed on 96 buildings on The University of Memphis main campus. In a study done by Boling (2009), 52 buildings were analyzed using the RVS method. Several of the buildings were divided into multiple structural systems (building types) in this study and in the study done by Boling (2009) to more accurately identify the structural type. As a result, data for 104 structures in Shelby County and 32 structures in Tipton County were recorded for this study. Boling (2009) recorded data for 69 structures during his research. A total of 301 structures were analyzed for this study. Table E-1 in Appendix D lists the building locations that were divided into multiple building types. Aerial photographs were used to identify the building footprint and corresponding locations for multiple building types.

3.1.1 Structural Load Resisting Systems

The RVS procedure identified 15 different building types for the 301 structures. All types of construction materials on the data collection forms were found in the field: concrete, masonry, steel, and wood. Table 3-1 lists the building type distribution. For the distribution of building types by county, refer to Appendix D.

Table 3-1. Building Type Distribution

Building Type	Number of Structures	Percent of Structures
C1	16	5%
C2	5	2%
C3	71	24%
PC1	4	1%
PC2	2	1%
RM1	31	10%
RM2	1	0%
S1	46	15%
S2	28	9%
S3	6	2%
S4	2	1%
S5	28	9%
URM	22	7%
W1	17	6%
W2	22	7%
Total	301	100%

3.1.2 Occupancy Types

HAZUS-MH MR3 utilizes 33 different occupancy classes; however, only 17 of these occupancy classes were identified within this study region. Table 3-2 lists the distribution of the occupancy classes. For the distribution of occupancy classes by county, refer to Appendix D.

Table 3-2. Occupancy Class Distribution

Occupancy Class	Occupancy Class Definition	Number of Structures	Percent of Structures
COM4	Professionals and Technical Services	2	1%
COM6	Hospitals	1	0%
COM7	Medical Office and Clinic	2	1%
COM8	Entertainment and Recreation	46	15%
COM9	Theatres	2	1%
COM10	Parking Garages	2	1%
EDU1	Grade Schools and Admin. Offices	33	11%
EDU2	Colleges and Universities	100	33%
GOV1	Government-General Services	1	0%
REL1	Churches and Non-Profit Organizations	77	26%
RES1	Single Family Dwellings	1	0%
RES3A	Duplex	1	0%
RES3C	5 to 9 Units	5	2%
RES3D	10 to 19 Units	7	2%
RES4	Temporary Lodging	1	0%
RES5	Institutional Dormitories	16	5%
RES6	Nursing Homes	4	1%
Total		301	100%

3.1.3 Construction Dates

The construction dates for the 301 structural building types greatly varied. Table 3-3 lists the distribution of the construction dates. For the distribution of construction dates by county, refer to Appendix D.

Table 3-3. Construction Date Distribution

Decade	Number of Structures	Percent of Structures
1850-1859	2	1%
1860-1869	0	0%
1870-1879	0	0%
1880-1889	0	0%
1890-1899	0	0%
1900-1909	0	0%
1910-1919	4	1%
1920-1929	4	1%
1930-1939	5	2%
1940-1949	6	2%
1950-1959	28	9%
1960-1969	54	18%
1970-1979	57	19%
1980-1989	51	17%
1990-1999	59	20%
2000-2009	22	7%
2010-2019	9	3%
Total	301	100%

3.1.4 Horizontal and Vertical Shape Irregularities

There are two shape performance modifiers on the RVS data collection form. These shape modifiers are horizontal (plan) irregularities and vertical irregularities. Table 3-4 lists the distribution for all of the combinations of the structures' shape qualities. For the distribution of shape qualities by county, refer to Appendix D.

Table 3-4. Shape Quality Distribution

Irregularity	Number of Structures	Percent of Structures
Plan	43	14%
Vertical	29	10%
No Irregularity	47	16%
Both Irregularities	182	60%
Total	301	100%

3.1.5 Building Height

There are three classifications of building height: low rise, mid rise, and high rise. Low rise structures are defined as having between 1 and 3 stories. Mid rise structures are defined as having between 4 and 7 stories. High rise buildings are defined as having more than 7 stories. All of these definitions are found in FEMA 154 (2002). Table 3-5 lists the distribution for the building heights. For the building heights by county, refer to Appendix D.

Table 3-5. Building Height Distribution

Height	Number of Structures	Percent of Structures
Low Rise	258	86%
Mid Rise	39	13%
High Rise	4	1%
Total	301	100%

3.1.6 S Scores

From the 301 structures evaluated using the RVS procedure, 80% of the structures received an S score lower than the established cut-off score of 2.0. This indicates that these 241 structures need a detailed evaluation from a professional engineer. However, 20% of the structures received a score higher than 2.0. These 60 structures are deemed safe to risk of life. Refer to Appendix D for final S scores of the entire study population.

3.2 HAZUS-MH MR3

HAZUS-MH MR3 is an extensive software package capable of performing several different loss estimates for different natural disasters. For the Level 2 analysis of the Earthquake Module, several preliminary tasks must first be completed. After the RVS data has been gathered, it must be organized using the data management program InCAST. Next, a study region must be defined within HAZUS-MH MR3. For this research, the study area is Shelby County and Tipton County, Tennessee. After this is accomplished, an earthquake scenario must be defined. For this study, user supplied ground motion maps were used. Lastly, the AEBM inventory is developed within HAZUS-MH MR3 by importing the InCAST database. At this point, the analysis can be run.

3.2.1 Inventory Collection and Survey Tool (InCAST)

InCAST is a data management program developed by FEMA which facilitates the development of a HAZUS-MH MR3 compatible database (HAZUS-MH MR3 2006b). The InCAST database is used to store the RVS data for the AEBM application. Although the analysis procedure specifies that the InCAST database be built after all RVS data is gathered from the field, this is not necessary. For this study, there were many field trips to different buildings throughout the study region. After each visit, the data that was gathered was put into the InCAST database. The database was slowly built over time after several field visits. The database was later imported into the AEBM inventory. Table 3-

6 shows the typical data that is stored within the InCAST database. Figure 3-1 shows a screen capture of the main building data window of InCAST.

Table 3-6. Sample InCAST Data Metrics

#	**Item**
1	ID Number
2	Name of the Building
3	Address of the Building
4	Latitude (decimal degrees)
5	Longitude (decimal degrees)
6	Census Tract Number
7	Occupancy Class
8	Building Structural Type
9	Total Building Area (sq.ft)
10	Year of Construction
11	Number of Stories
12	Soil Type
13	Landslide Susceptibility
14	Liquefaction Susceptibility
15	Ground Water Depth (ft)
16	Seismic Design Level
17	Earthquake Design Year
18	Horizontal Shape Configuration
19	Vertical Shape Configuration

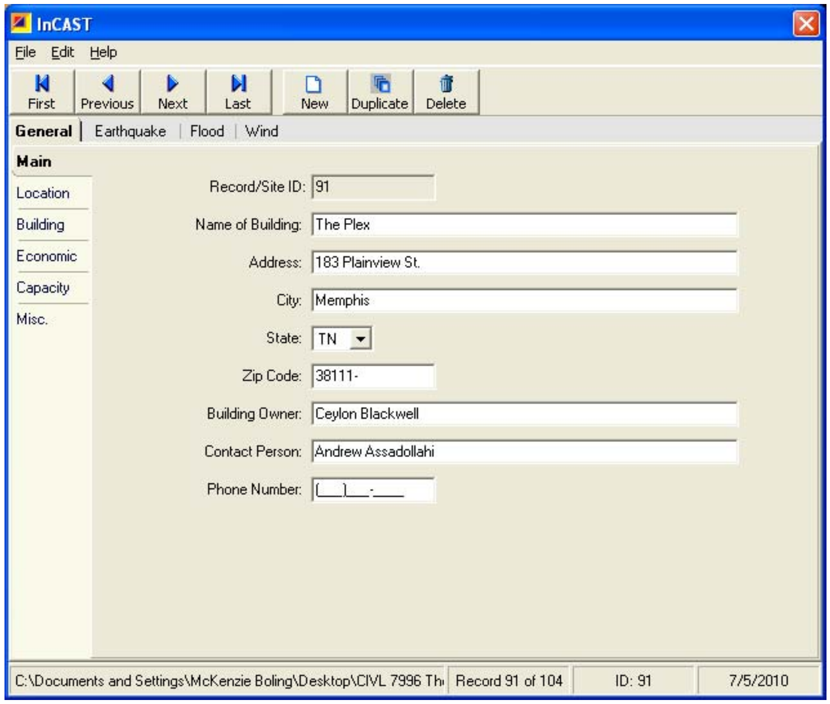


Figure 3-1. InCAST Screen Capture

3.2.2 Defining a Study Region

HAZUS-MH MR3 is capable of multiple levels of aggregation. A region can be created by state, county, or census tract. The smallest region is at the census tract level (FEMA 433 2004). The census tract level was chosen for this study because the smaller the aggregation level, the more detail HAZUS-MH MR3 can provide. Initially, the addresses for all locations were searched using Google Earth to obtain their latitudes and longitudes. The latitudes and longitudes were then assembled as a point coverage in ArcGIS v. 9.2. Aerial photographs for Shelby and Tipton Counties were added as a layer on the map to make sure the points fell approximately in the center of each building or structure. The census tracts were obtained by merging the point coverage layer of the structure locations with the census tract layer. Table 3-7 shows a listing of the 80 census tracts where the 242 building sites are located. For the census tracts of Shelby and Tipton

Counties individually, refer to Appendix D. Figure. 3-2 depicts the distribution of census tracts within the entire study region as well as the location of all the structures. For structure location distributions from Mize (2006), Boling (2009), and this project, refer to Appendix D.

Table 3-7 Census Tracts Identified in Study Region

ID	Census Tract	ID	Census Tract	ID	Census Tract
1	47157000200	28	47157009000	55	47157021341
2	47157000500	29	47157009200	56	47157021430
3	47157000800	30	47157009400	57	47157021510
4	47157001200	31	47157009500	58	47157021520
5	47157001900	32	47157009700	59	47157021611
6	47157002100	33	47157009900	60	47157021620
7	47157002800	34	47157010120	61	47157021721
8	47157003100	35	47157010210	62	47157021723
9	47157003200	36	47157010710	63	47157021732
10	47157003300	37	47157010900	64	47157021741
11	47157003600	38	47157020300	65	47157021752
12	47157004200	39	47157020400	66	47157021900
13	47157004600	40	47157020522	67	47157022010
14	47157005000	41	47157020530	68	47157022111
15	47157005300	42	47157020541	69	47157022112
16	47157006400	43	47157020610	70	47157022120
17	47157006500	44	47157020621	71	47157022220
18	47157006700	45	47157020622	72	47157022321
19	47157006900	46	47157020631	73	47157022330
20	47157007000	47	47157020632	74	47167040100
21	47157007100	48	47157020651	75	47167040301
22	47157007300	49	47157020830	76	47167040500
23	47157007400	50	47157021010	77	47167040601
24	47157007500	51	47157021121	78	47167040602
25	47157007810	52	47157021137	79	47167040700
26	47157008600	53	47157021200	80	47167040800
27	47157008700	54	47157021310		

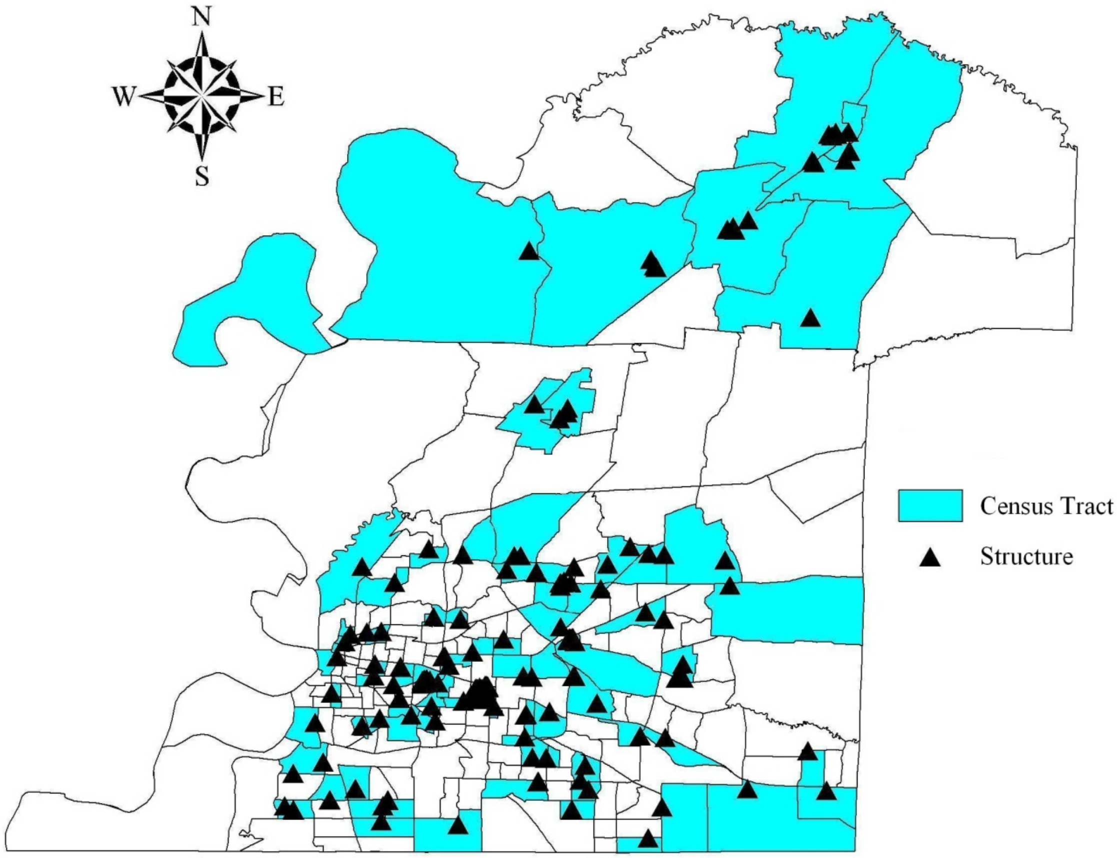


Figure 3-2. Census Tract Distribution within Study Region

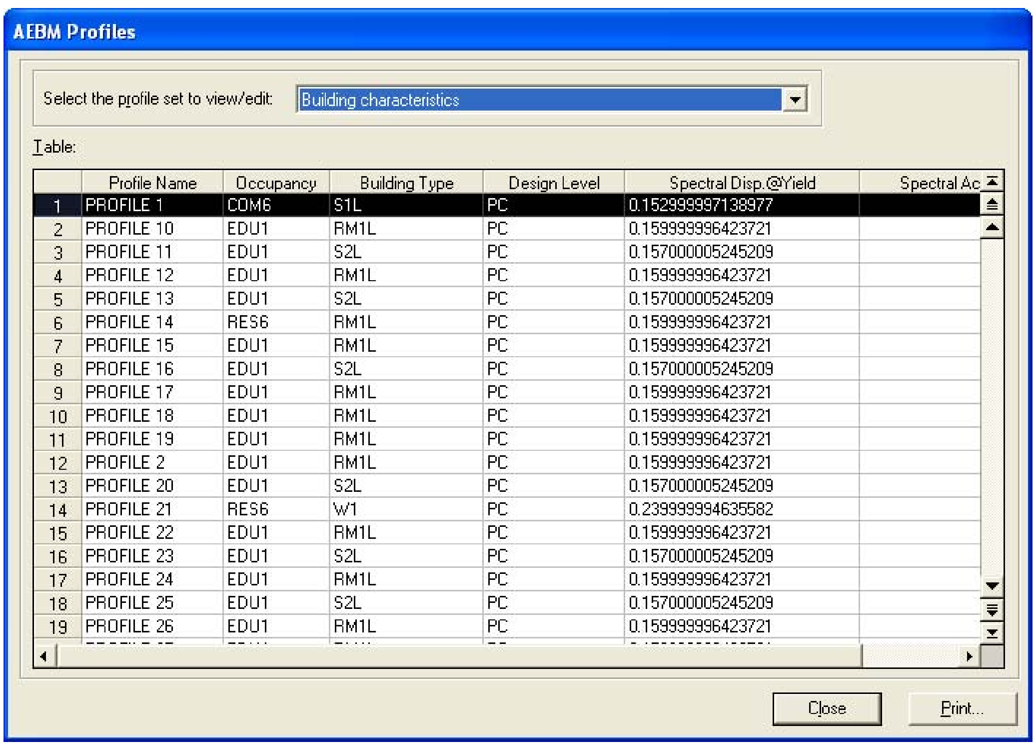
3.2.3 Defining an Earthquake Scenario

This study employed not only ground motion maps from the USGS but also ground motion maps that include the affect of local geology developed for the greater Memphis area (Cramer 2006, Cramer et al. 2004, and Frankel et al. 2002). The USGS ground motion maps were employed in this study only using a M7.7 earthquake scenario located northwest of Memphis.

Two scenario earthquakes were modeled in Cramer's research: a magnitude 7.7 on the southwest arm of the New Madrid seismic zone (Cottonwood Grove Fault) and a magnitude 6.5 on the southern end of the southeast arm at Marked Tree, Arkansas. The probabilistic ground motions were for a 2% probability of being exceeded in 50 years. Since the data provided by Cramer was originally in text format, a procedure was developed in a previous study to convert the text data into a HAZUS-MH MR3 compatible map format. Cramer's data is the most up-to-date representation of the ground motions for the mid-south region and has 304 unique PGA values for a magnitude 7.7 earthquake. Cramer's Tipton County data has 335 unique PGA values for a magnitude 7.7 earthquake. There are only four unique PGA values for Shelby County and Tipton County on the USGS ground motion map. Cramer's data was employed in this study for both Shelby County and Tipton County. See Appendix C for all USGS ground motion maps as well as ground motion maps developed by Cramer.

3.2.4 Advanced Engineering Building Module (AEBM)

The AEBM inventory is ready to be generated once the InCAST database is completed and the study region has been established. Since InCAST was developed before the earthquake module in HAZUS-MH, not all of the InCAST fields can be mapped into the AEBM (Boling 2009). Building profiles should be developed by identifying the building type, occupancy class, and seismic design level (HAZUS-MH MR3 2006). The profiles must match the appropriate structures in the AEBM inventory so the proper fragility curve will be used in the analysis. A building profile was created for each of the 301 structures for this study. Figure 3-3 shows a screen capture of the AEBM profile window.



	Profile Name	Occupancy	Building Type	Design Level	Spectral Disp.@Yield	Spectral Ac
1	PROFILE 1	COM6	S1L	PC	0.152999997138977	
2	PROFILE 10	EDU1	RM1L	PC	0.159999996423721	
3	PROFILE 11	EDU1	S2L	PC	0.157000005245209	
4	PROFILE 12	EDU1	RM1L	PC	0.159999996423721	
5	PROFILE 13	EDU1	S2L	PC	0.157000005245209	
6	PROFILE 14	RES6	RM1L	PC	0.159999996423721	
7	PROFILE 15	EDU1	RM1L	PC	0.159999996423721	
8	PROFILE 16	EDU1	S2L	PC	0.157000005245209	
9	PROFILE 17	EDU1	RM1L	PC	0.159999996423721	
10	PROFILE 18	EDU1	RM1L	PC	0.159999996423721	
11	PROFILE 19	EDU1	RM1L	PC	0.159999996423721	
12	PROFILE 2	EDU1	RM1L	PC	0.159999996423721	
13	PROFILE 20	EDU1	S2L	PC	0.157000005245209	
14	PROFILE 21	RES6	W1	PC	0.239999994635582	
15	PROFILE 22	EDU1	RM1L	PC	0.159999996423721	
16	PROFILE 23	EDU1	S2L	PC	0.157000005245209	
17	PROFILE 24	EDU1	RM1L	PC	0.159999996423721	
18	PROFILE 25	EDU1	S2L	PC	0.157000005245209	
19	PROFILE 26	EDU1	RM1L	PC	0.159999996423721	

Figure. 3-3. AEBM Profile Window Screen Capture

3.2.5 HAZUS-MH MR3 Loss Estimation

Three earthquake scenarios were defined, a magnitude 7.7 on the southwest arm of the New Madrid seismic zone (Cottonwood Grove Fault) using Cramer's ground motion maps and the USGS-supplied ground motion maps, and a magnitude 6.5 on the southern end of the southwest arm at Marked Tree, Arkansas using Cramer's ground motion maps. The scenario must be named and four ground motion maps must be supplied for each scenario: 0.3 s Spectral Acceleration (Sa), 0.1 s Sa, Peak Ground Velocity (PGV), and Peak Ground Acceleration (PGA). Table 3-8, Table 3-9, and Table 3-10 list the maximum, minimum, and average ground motions for each of the three scenarios. Observing Table 3-9 and Table 3-10, it is seen that for the 301 structure data set, the ground motion values from Cramer's data are almost always larger than the corresponding values from the USGS data.

Table 3-8. Ground Motions: Magnitude 6.5, Cramer Data

Ground Motion	Minimum	Maximum	Average
0.3 s Sa (g)	0.20	0.41	0.26
0.1 s Sa (g)	0.07	0.11	0.11
PGA (g)	0.11	0.29	0.17

Table 3-9. Ground Motions: Magnitude 7.7, Cramer Data

Ground Motion	Minimum	Maximum	Average
0.3 s Sa (g)	0.48	0.92	0.60
0.1 s Sa (g)	0.43	0.62	0.53
PGA (g)	0.30	0.62	0.40

Table 3-10. Ground Motions: Magnitude 7.7, USGS Data

Ground Motion	Minimum	Maximum	Average
0.3 s Sa (g)	0.50	0.90	0.58
0.1 s Sa (g)	0.30	0.50	0.33
PGA (g)	0.25	0.55	0.38

Based upon the ground motion parameters taken from the maps and the structure data from InCAST, HAZUS-MH MR3 calculates damage state probabilities for each structure. The damage state probabilities are defined as: none, slight, moderate, extensive, and complete. The damage states are calculated as structural damage (SS), non-structural damage: drift sensitive (NSD), and acceleration sensitive (NSA). Appendix E gives the definition for each damage state according to the building type.

Three important factors about the structures are calculated from the damage state probabilities. An "Immediate Occupancy" (IO) factor is computed as the sum of the "none" and "slight" structural damage (SS) state probabilities. The IO factor represents the probability that immediately following an earthquake; a building will be suitable for occupancy (Boling 2009). A HAZUS-MH MR3-based S score (S_H score) was calculated from the *P*(major damage) using Equation (2.2), where the *P*(major damage) of each structure was calculated as the summation of "extensive" and "complete" damage states. A building replacement cost (*BRC*) factor is computed using all of the damage state probabilities. The *BRC* factor is a representation of a structure's value that will need to be provided for repair.

An example of the *BRC* calculation for Structure 1, which has the occupancy class of REL1, is seen below. Table 3-11 lists the SS, NSD, and NSA damage state probabilities calculated by HAZUS-MH MR3. Table 3-12 lists the repair cost ratios for the SS, NSD, and NSA performance groups for REL1 as given in HAZUS-MH MR3 Earthquake Model Technical Manual (2006a).

Table 3-11. Damage State Probabilities (%) for Structure 1

Performance Group	None	Slight	Moderate	Extensive	Complete
SS	0.791	0.175	0.033	0.001	0
NSD	0.842	0.119	0.038	0.001	0
NSA	0.68	0.252	0.063	0.004	0

Table 3-12. Repair Cost Ratios for REL1

Performance Group	Slight	Moderate	Extensive	Complete
SS	0.3	2	9.9	19.8
NSD	0.8	3.3	16.3	32.6
NSA	0.9	4.7	14.3	47.6

Equation (2.1) becomes:

$BRC_1 = BRC_{\mathrm{SS}}$

$BRC_1 = (0.3)(0.175) + (2)(0.033) + (9.9)(0.001) + (19.8)(0) = 0.1284$

$BRC_2 = BRC_{\mathrm{NSD}}$

$BRC_2 = (0.8)(0.119) + (3.3)(0.038) + (16.3)(0.001) + (32.6)(0) = 0.2369$

$BRC_3 = BRC_{\mathrm{NSA}}$

$BRC_3 = (0.9)(0.252) + (4.7)(0.063) + (14.3)(0.004) + (47.6)(0) = 0.5801$

$BRC = BRC_1 + BRC_2 + BRC_3 = 0.9454$

$\boldsymbol{BRC = 0.95}$

All of the structures were prioritized according to the S score, IO factor, and *BRC* factor. Each structure was assigned a rank based upon the three performance metrics. Some structures share the same rank due to same numeric values for the S score, IO factor, and *BRC* factor. There are 42 unique S scores for the 301 structures. For the magnitude 6.5 scenario (based upon Cramer's data), there are 117 unique IO factors and 142 unique *BRC* factors. For the magnitude 7.7 scenario, based upon Cramer's data maps, there are 96 unique IO factors and 200 unique *BRC* factors. For the magnitude 7.7 scenario, based upon the USGS data maps, there are 108 unique IO factors and 151 unique *BRC* factors. The structures were sorted according to three levels: first, by the *BRC* factor; secondly, by the IO factor; and lastly, by the S score. This is because the *BRC* factor is the most complex calculation producing the most unique values, followed by the IO factor (Boling 2009). However, even after the data based upon these metrics, some structures share the same ranking.

3.2.6 Magnitude 6.5 (Cramer Data)

For this scenario, Cramer's site-specific ground motion maps for a magnitude 6.5 earthquake on the southern end of the southwest arm at Marked Tree, Arkansas were imported into HAZUS. Figure 3-4 shows the trend of the IO factor decreasing as the *BRC* factor increases. Figure 3-5 shows the trend of the declining S scores as the *BRC* increases. With any data set, there will be outliers. Generally, as a data set gets larger, one can expect to have a larger number of outliers. Figure 3-5 illustrates these outliers. A close examination of the right side of Figure 3-5 shows two of these outlier data points that fall on the cut-off score but have high associated *BRC* values. The difference between S score, the *BRC* factor may be due to performance modification factors such as building irregularities (Boling, 2009). In this analysis, HAZUS-MH MR3 does not account for horizontal and vertical building irregularities. However, building irregularities have a severe negative impact on the S score.

Figure 3-6 shows the relationship between S scores and S_H scores. This plot shows more S_H scores than S scores above the cut-off score. Some structures' S_H scores were omitted because they were calculated as infinite. This occurs when both the "extensive" and "complete" damage probabilities are zero. Table 3-13 summarizes the means and medians of S scores and S_H scores. It can be said for this earthquake scenario, the RVS procedure seems to be conservative.

Table 3-13. Mean and Median (Cramer M6.5)

	S Score	**S_H Score**	**S Score ($\geq$ 2.0)**	**S_H Score ($\geq$ 2.0)**	**S Score (< 2.0)**	**S_H Score (< 2.0)**
Mean	0.8	1.7	2.9	2.5	0.3	1.4
Median	0.5	1.5	2.3	2.7	-0.1	1.4

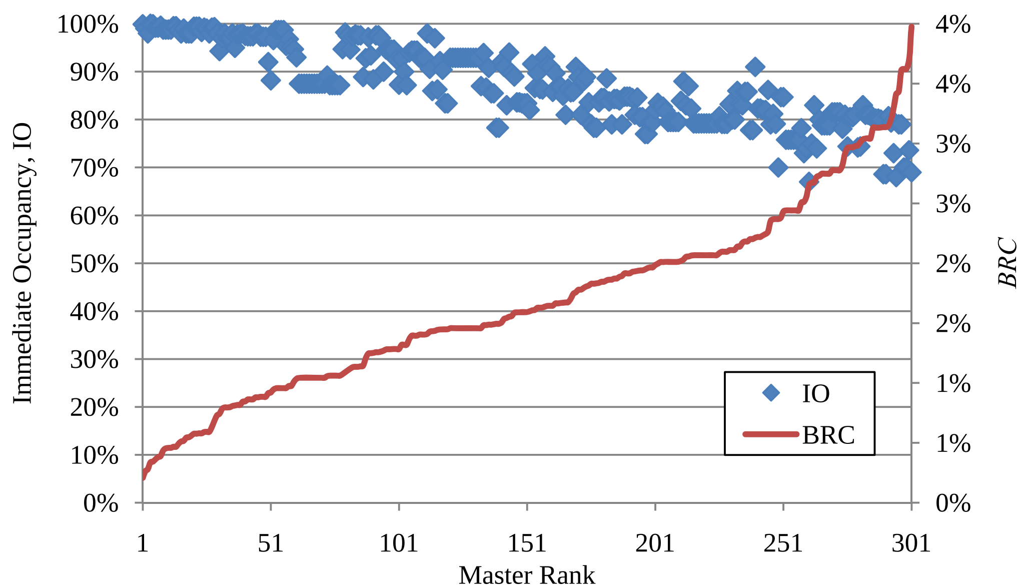


Figure 3-4. Comparison of Master Rank to IO Factor and *BRC* Factor (Cramer M6.5)

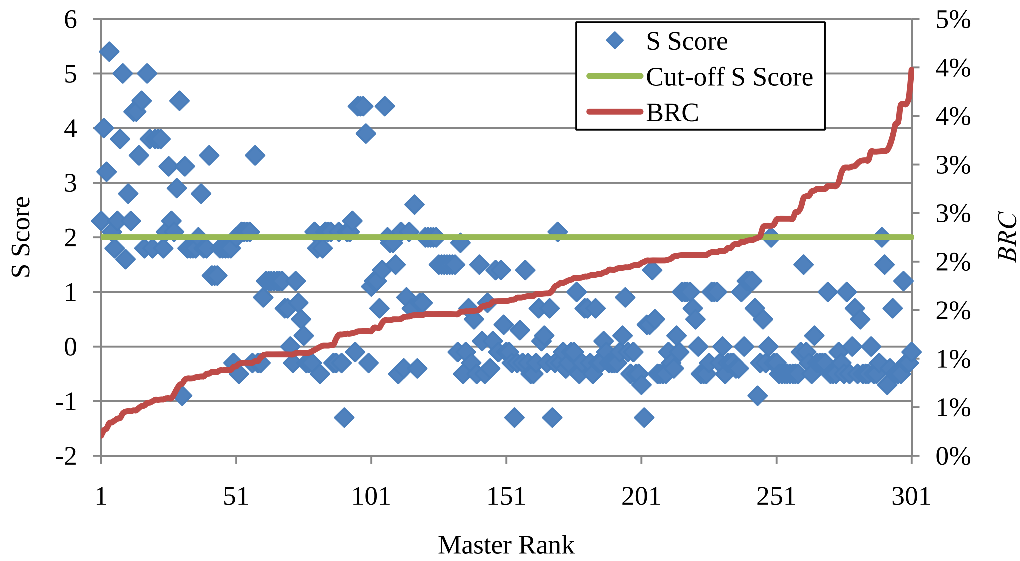


Figure 3-5. Comparison of Master Rank to S Score and *BRC* Factor (Cramer M6.5)

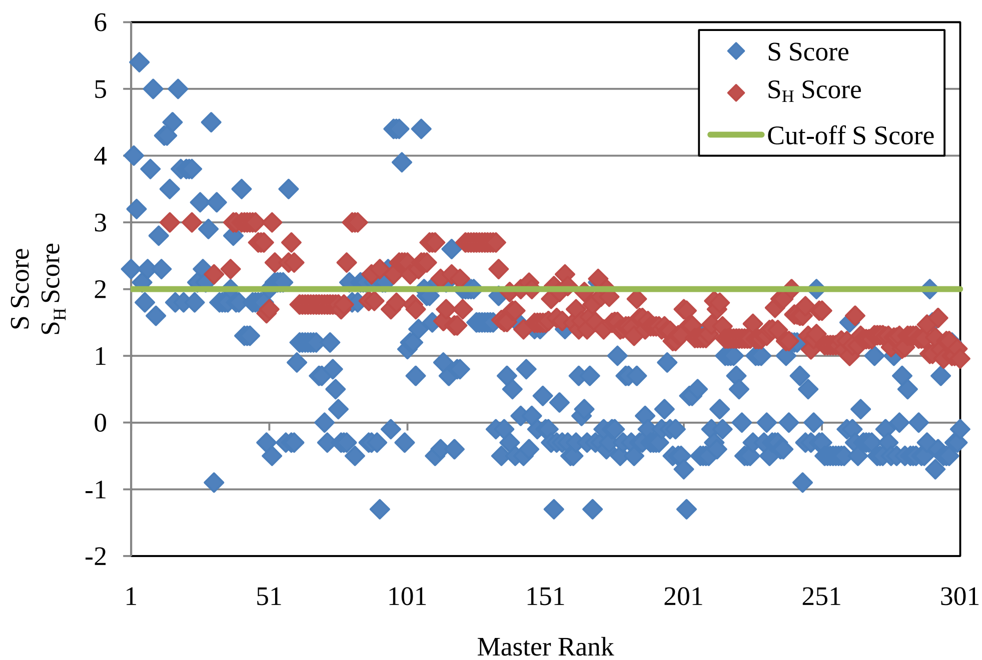


Figure 3-6. Comparison Master Rank to S Score to S_H Score (Cramer M6.5)

Analysis of variance tests and Tukey's Multiple-Comparison tests were performed on *BRC* factors, IO factors, scaled S scores, and scaled S_H scores for construction date time periods and building type categories, for a 95% level of significance. The null hypotheses for the construction date time periods (pre-1931, 1931-1950, 1951-1970, 1971-1990, and 1991-2010) are given as:

H_o for *BRC*:

> There is no statistically significant difference between the mean *BRC* factors based on Cramer's ground motion data, for the construction date time periods, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for IO:

> There is no statistically significant difference between the mean IO factors based on Cramer's ground motion data, for the construction date time periods, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S scores:

> There is no statistically significant difference between the mean scaled S scores based on Cramer's ground motion data, for the construction date time periods, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S_H scores:

> There is no statistically significant difference between the mean scaled S_H scores based on Cramer's ground motion data, for the construction date time periods, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

Table 3-14 summarizes the ANOVA tests for construction date time period.

Table 3-14. ANOVA Summary for Construction Dates (Cramer M6.5)

Factor	***P-value***	$\boldsymbol{F_{calc}}$	$\boldsymbol{F_{crit}}$	**Relationship**	**Rejection Statement**
BRC	9.23E-31	47.37	2.402	$F_{calc} > F_{crit}$	Reject H_o
IO	8.67E-45	77.24	2.402	$F_{calc} > F_{crit}$	Reject H_o
Scaled S Score	1.42E-40	67.85	2.402	$F_{calc} > F_{crit}$	Reject H_o
Scaled S_H	2.11E-18	26.74	2.402	$F_{calc} > F_{crit}$	Reject H_o

By rejecting the null hypotheses, it is concluded that at least one of the means is different from the others for the construction date time periods. The P-value is the actual probability of obtaining a test statistic at least as extreme as the one that was actually observed, when assuming the null hypothesis is true. The P-value is the actual probability that the null hypothesis should not be rejected. Therefore, it represents that for the construction date time periods; the null hypotheses will be rejected for essentially 100% of samples for a magnitude 6.5 earthquake based on Cramer's data. Tukey's Multiple Comparison Procedure will determine which categories are significantly different from the others. Table 3-15 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the *BRC* factors of the construction date time periods for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-15. Tukey Multiple Comparison for Construction Date *BRC* (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1991-2010	0.008156	1	5 vs 4	0.000942	<	0.004088
Pre-1931	0.016948	2	5 vs 3	0.001020	<	0.002335
1951-1970	0.018982	3	5 vs 2	0.003054	<	0.005204
1931-1950	0.019060	4	5 vs 1	0.011847	>	0.002513
1971-1990	0.020002	5	4 vs 3	0.000078	<	0.004157
			4 vs 2	0.002112	<	0.006238
			4 vs 1	0.010905	>	0.004259
			3 vs 2	0.002034	<	0.005259
			3 vs 1	0.010826	>	0.002624
			2 vs 1	0.008792	>	0.005340

Applying Tukey's procedure to the construction date time period mean *BRC* factors concludes that the data corresponding to Counter 1 (1991-2010 time period) has a significantly lower mean *BRC* compared to each of the other time periods individually.

Table 3-16 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the IO factors of the construction date time periods for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-16. Tukey Multiple Comparison for Construction Date IO (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1951-1970	0.835467	1	5 vs 4	0.113070	>	0.040124
Pre-1931	0.839000	2	5 vs 3	0.134638	>	0.023673
1971-1990	0.841748	3	5 vs 2	0.137386	>	0.050307
1931-1950	0.863316	4	5 vs 1	0.140919	>	0.024719
1991-2010	0.976386	5	4 vs 3	0.021568	<	0.038509
			4 vs 2	0.024316	<	0.058765
			4 vs 1	0.027849	<	0.039160
			3 vs 2	0.002748	<	0.049029
			3 vs 1	0.006281	<	0.022001
			2 vs 1	0.003533	<	0.049542

Applying Tukey's procedure to the construction date time period IO data concludes that the data corresponding to Counter 5 (1991-2010 time period) has a significantly higher mean IO compared to each of the other time periods individually. This makes sense because the *BRC* factor and IO factor are computed from the HAZUS output and as the *BRC* increases, the IO tends to decrease.

Table 3-17 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S scores of the construction date time periods for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-17. Tukey Multiple Comparison for Construction Date Scaled S Score (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1971-1990	10.1757	1	5 vs 4	1.382406	>	0.705423
1951-1970	10.2544	2	5 vs 3	2.013506	>	0.884458
Pre-1931	10.4636	3	5 vs 2	2.222698	>	0.434580
1931-1950	11.0947	4	5 vs 1	2.301467	>	0.416207
1991-2010	12.4771	5	4 vs 3	0.631100	<	1.033160
			4 vs 2	0.840292	>	0.688486
			4 vs 1	0.919061	>	0.677039
			3 vs 2	0.209192	<	0.871010
			3 vs 1	0.287961	<	0.861990
			2 vs 1	0.078769	<	0.386808

Applying Tukey's procedure to the construction date time period scaled S score data concludes that the data corresponding to Counter 5 (1991-2010 time period) has a significantly higher scaled S score mean compared to each of the other time periods individually. This is consistent with the Tukey results from Table 3-16 which shows that the mean IO factor for the 1991-2010 time period is significantly higher than the mean IO factors for time periods. Also, the data corresponding to Counter 4 (1931-1950 time period) has a significantly higher scaled S score mean when compared to the 1971-1990 time period and the 1951-1970 time period.

Table 3-18 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S_H scores of the construction date time periods for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-18. Tukey Multiple Comparison for Construction Date Scaled S_H Score (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1951-1970	11.58053	1	5 vs 4	0.886540	>	0.409321
Pre-1931	11.64748	2	5 vs 3	1.026040	>	0.296264
1971-1990	11.65656	3	5 vs 2	1.035128	>	0.468077
1931-1950	11.79606	4	5 vs 1	1.102070	>	0.301470
1991-2010	12.68260	5	4 vs 3	0.139500	<	0.330533
			4 vs 2	0.148587	<	0.490485
			4 vs 1	0.215529	<	0.335208
			3 vs 2	0.009087	<	0.401004
			3 vs 1	0.076030	<	0.180534
			2 vs 1	0.066942	<	0.404866

Applying Tukey's procedure to the construction date time period scaled S_H score data concludes that the data corresponding to Counter 5 (1991-2010 time period) has a significantly higher scaled S_H score mean compared to each of the other time periods individually. This result is consistent with the results from Table 3-17.

These conclusions are valid for approximately 95% of samples, when many samples are gathered. The results from Tukey's Multiple Comparison Test on the construction date time periods for the mean *BRC*, IO, scaled S score, and scaled S_H score for a magnitude 6.5 earthquake based upon Cramer's data seem to be consistent. The mean *BRC* is significantly lower for the 1991-2010 time period while the mean IO, scaled S score, and scaled S_H score is significantly higher for this same time period. This indicates that structures built in this time period tend to perform better than structures built in the other time periods. This seems logical since these are newer structures which have been designed based upon the more strict seismic provisions. The only inconsistency is seen in Table 3-17 in which the data corresponding to Counter 4 (1931-1950 time period) has a significantly higher scaled S score mean when compared to the 1971-1990 time period and the 1951-1970 time period for the scaled S score. This could be due to the slight ambiguity surrounding the RVS method.

The null hypotheses for the building type categories (concrete, pre-cast concrete, reinforced concrete, steel, unreinforced masonry, and wood) are given as:

H_o for *BRC*:

> There is no statistically significant difference between the mean *BRC* factors based on Cramer's ground motion data, for the building type categories, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for IO:

> There is no statistically significant difference between the mean IO factors based on Cramer's ground motion data, for the building type categories, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S scores:

> There is no statistically significant difference between the mean scaled S scores based on Cramer's ground motion data, for the building type categories, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S_H scores:

> There is no statistically significant difference between the mean scaled S_H scores based on Cramer's ground motion data, for the building type categories, for a magnitude 6.5 earthquake on the southwest arm of the New Madrid seismic zone.

Table 3-19 summarizes the ANOVA tests for building type categories.

Table 3-19. ANOVA Summary for Building Types (Cramer M6.5)

Factor	***P-value***	F_{calc}	F_{crit}	**Relationship**	**Rejection Statement**
BRC	4.66E-20	23.74	2.245	$F_{calc} > F_{crit}$	Reject H_o
IO	2.02E-26	32.58	2.245	$F_{calc} > F_{crit}$	Reject H_o
Scaled S Score	1.67E-15	17.91	2.245	$F_{calc} > F_{crit}$	Reject H_o
Scaled S_H	2.69E-26	31.27	2.245	$F_{calc} > F_{crit}$	Reject H_o

By rejecting the null hypotheses, it is concluded that at least one of the means is different from the others for the building type categories. The P-value is the actual probability that the null hypothesis should not be rejected. Therefore, it represents that for the building type categories, the null hypotheses will be rejected for essentially 100% of samples for a magnitude 6.5 earthquake based on Cramer's data. Tukey's Multiple Comparison Procedure will determine which categories are significantly different from the others. Table 3-20 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the *BRC* factors of the building type categories for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-20. Tukey Multiple Comparison for Building Type *BRC* (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
Wood	0.012459	1	6 vs 5	0.001211	<	0.008576
Steel	0.014399	2	6 vs 4	0.011378	>	0.008284
Concrete	0.017648	3	6 vs 3	0.011444	>	0.007846
RM	0.017713	4	6 vs 2	0.014692	>	0.007806
URM	0.027880	5	6 vs 1	0.016632	>	0.008166
PC	0.029091	6	5 vs 4	0.010167	>	0.005157
			5 vs 3	0.010233	>	0.004419
			5 vs 2	0.013481	>	0.004349
			5 vs 1	0.015421	>	0.004965
			4 vs 3	0.000066	<	0.003822
			4 vs 2	0.003314	<	0.003740
			4 vs 1	0.005254	>	0.004441
			3 vs 2	0.003248	>	0.002631
			3 vs 1	0.005188	>	0.003558
			2 vs 1	0.001940	<	0.003470

Applying Tukey's procedure to the building type category *BRC* data concludes that the data corresponding to Counter 5 (URM) has a significantly higher mean *BRC* when compared to each of the other building types individually. The data corresponding to Counter 6 (PC) has a significantly higher *BRC* mean compared to each of the other building types except when compared to URM. Table 3-20 also shows that Concrete structures have a significantly higher *BRC* when compared to Steel and Wood structures; and RM has a significantly higher mean *BRC* than Wood. These results could be outliers or could have more error in the calculations due to unequal sample sizes.

Table 3-21 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the IO factors of the building type categories for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-21. Tukey Multiple Comparison for Building Type IO (Cramer M6.5)

Groups	**Average**	**Counter**	**Comparison**	**Difference**		**Rejection Region**
PC	0.743333	1	6 vs 5	0.042275	>	0.034690
URM	0.803409	2	6 vs 4	0.081070	>	0.044398
Concrete	0.830337	3	6 vs 3	0.116202	>	0.035567
RM	0.865469	4	6 vs 2	0.143129	>	0.049632
Steel	0.904264	5	6 vs 1	0.203205	>	0.081627
Wood	0.946538	6	5 vs 4	0.038795	>	0.037386
			5 vs 3	0.073927	>	0.026298
			5 vs 2	0.100855	>	0.043473
			5 vs 1	0.160930	>	0.078036
			4 vs 3	0.035132	<	0.038201
			4 vs 2	0.062060	>	0.051552
			4 vs 1	0.122135	>	0.082809
			3 vs 2	0.026928	<	0.044176
			3 vs 1	0.087004	>	0.078430
			2 vs 1	0.060076	<	0.085729

Applying Tukey's procedure to the building type category IO data concludes that the data corresponding to Counter 5 (Steel) has a significantly higher IO mean compared to each of the other building types individually. The data corresponding to Counter 6 (Wood) has a significantly higher IO mean compared to each of the other building types. Table 3-21 also shows that Reinforced Masonry structures have a significantly higher IO when compared to PC and URM structures; and Concrete structures have a significantly higher mean IO than PC. These results seem to be consistent with the results from Table 3-21.

Table 3-22 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S scores of the building types for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-22. Tukey Multiple Comparison for Building Type Scaled S Score (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
URM	9.840909	1	6 vs 5	1.314336	>	0.643921
PC	10.216667	2	6 vs 4	1.349279	>	0.824119
Concrete	10.272826	3	6 vs 3	1.973328	>	0.660203
RM	10.896875	4	6 vs 2	2.029487	>	1.515188
Steel	10.931818	5	6 vs 1	2.405245	>	0.921275
Wood	12.246154	6	5 vs 4	0.034943	<	0.693970
			5 vs 3	0.658992	>	0.488150
			5 vs 2	0.715152	<	1.448522
			5 vs 1	1.090909	>	0.806952
			4 vs 3	0.624049	<	0.709104
			4 vs 2	0.680208	<	1.537126
			4 vs 1	1.055966	>	0.956927
			3 vs 2	0.056159	<	1.455833
			3 vs 1	0.431917	<	0.820003
			2 vs 1	0.375758	<	1.591330

Tukey's procedure for the building type category scaled S score data concludes that the data corresponding to Counter 6 (Wood) has a significantly higher mean scaled S score when compared to each of the other building types individually. This is consistent with the results from Table 3-21, which shows that Wood structures have a significantly higher mean IO. Table 3-22 also shows that Reinforced Masonry structures have a significantly higher scaled S score when compared to URM structures; and Steel structures have a significantly higher mean scaled S score than URM and Concrete. These results could be outliers or could have more error in the calculations due to unequal sample sizes.

Table 3-23 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S_H scores of the building types for a magnitude 6.5 earthquake based upon Cramer's data.

Table 3-23. Tukey Multiple Comparison for Building Type Scaled S_H Score (Cramer M6.5)

Groups	Average	Counter	Comparison	Difference		Rejection Region
PC	11.137404	1	6 vs 5	0.716978	>	0.227226
URM	11.324079	2	6 vs 4	1.010201	>	0.290814
Concrete	11.547710	3	6 vs 3	1.027077	>	0.232972
RM	11.564587	4	6 vs 2	1.250708	>	0.325099
Steel	11.857809	5	6 vs 1	1.437383	>	0.534678
Wood	12.574787	6	5 vs 4	0.293223	>	0.244888
			5 vs 3	0.310099	>	0.172258
			5 vs 2	0.533731	>	0.284756
			5 vs 1	0.720405	>	0.511153
			4 vs 3	0.016876	<	0.250228
			4 vs 2	0.240508	<	0.337679
			4 vs 1	0.427183	<	0.542419
			3 vs 2	0.223632	<	0.289362
			3 vs 1	0.410306	<	0.513733
			2 vs 1	0.186675	<	0.561547

Tukey's procedure for the building type category scaled S_H score data concludes that the data corresponding to Counter 6 (Wood) has a significantly higher scaled S_H score mean compared to each of the other building types individually. Also, Table 3-23 shows that the data corresponding to Counter 5 (Steel) has a significantly higher scaled S_H score mean compared to each of the other building types individually. These results are reasonably consistent with the results from Table 3-21 and Table 3-22; however, Table 3-23 shows that Steel structures have a higher mean scaled S_H score compared to all other building types, whereas Table 3-22 shows that Steel structures are only significantly superior to URM and Concrete structures.

All of these results are valid for approximately 95% of samples, when many samples are gathered. The results from Tukey's Multiple Comparison Test on the building type categories for the mean *BRC*, IO, scaled S score, and scaled S_H score for a magnitude 6.5 earthquake based upon Cramer's data seem to be fairly consistent; however, not as consistent as the results from the construction date time periods. The mean *BRC* is significantly higher for Pre-cast concrete and Un-reinforced Masonry structures. Steel and Wood structures tend to have the significantly highest mean IO, scaled S score, and scaled S_H score when compared to the other building type categories. There are more outliers with this set of data than with the construction date time period data however.

A potential application, discussed earlier, of emergency planning in case of a natural disaster (seismic or otherwise) is demonstrated in Figure 3-7. Using ArcGIS v. 9.2, a population density map for the study region was overlain by a measure of seismic performance.

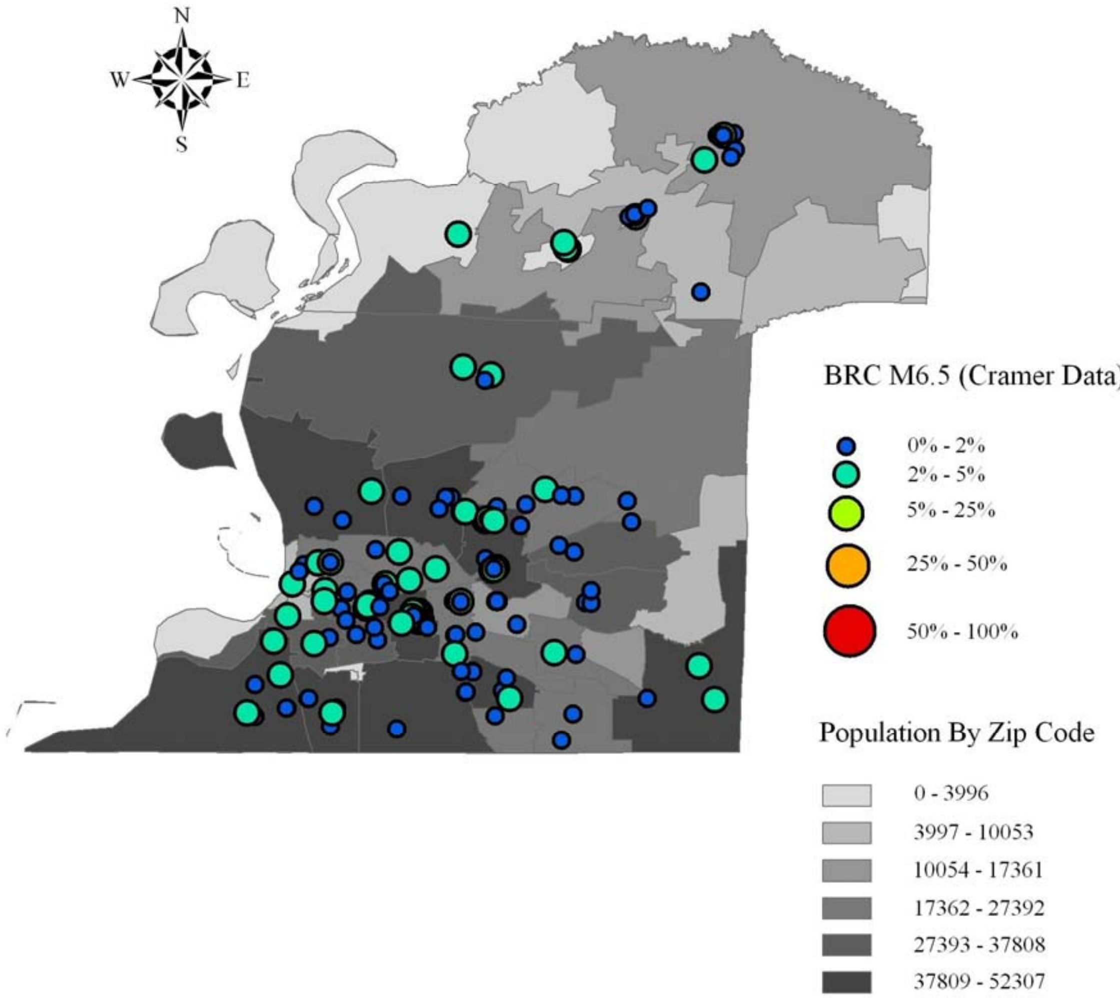


Figure 3-7. Population Distribution of *BRC* Factors (Cramer M6.5)

3.2.7 Magnitude 7.7 (Cramer Data)

For this scenario, Cramer's ground motion maps for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone (Cottonwood Grove Fault) were imported into HAZUS. Figure 3-8 shows the trend of the *BRC* factor increasing as the IO decreases. Figure 3-9 depicts the *BRC* factor increasing as the S scores decrease. Figure 3-10 shows the relationship between the S scores and the S_H scores. The RVS procedure predicts significantly more S scores above the cut-off score than the S_H scores calculated from HAZUS-MH-MR3. Table 3-24 summarizes the means and medians of S scores and S_H scores. Based upon the values from this data set; it can be said for this earthquake scenario, the RVS procedure seems to not be conservative. That is, the RVS procedure produced a higher mean S score when compared to the HAZUS-S_H score. This means that the RVS procedure produced higher S scores for some structures while HAZUS produced lower S_H scores for the same structures.

Table 3-24. Mean and Median (Cramer M7.7)

	S Score	**S_H Score**	**S Score (≥ 2.0)**	**S_H Score (≥ 2.0)**	**S Score (< 2.0)**	**S_H Score (< 2.0)**
Mean	0.8	0.5	2.9	2.5	0.3	0.4
Median	0.5	0.1	2.3	2.2	-0.1	0.1

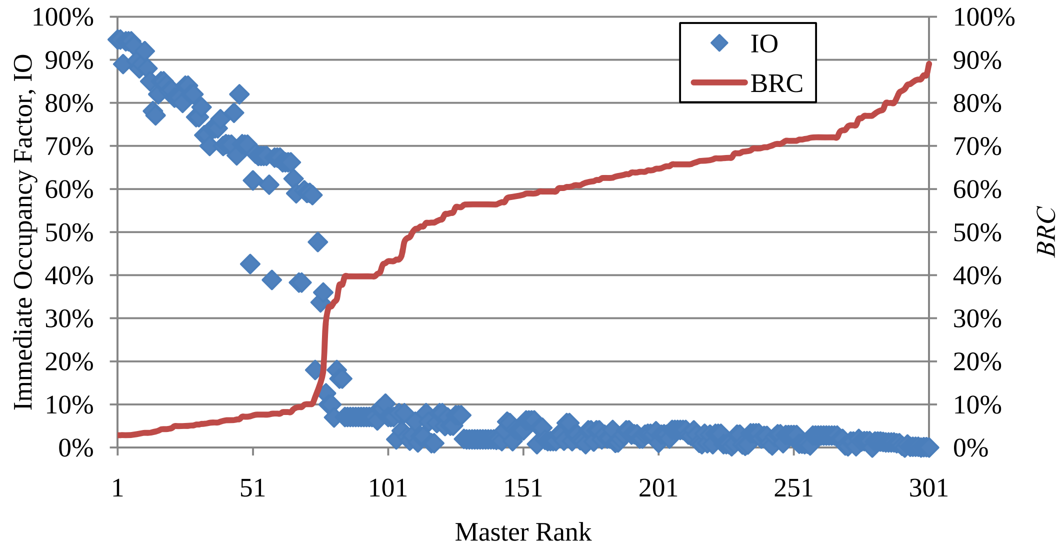


Figure 3-8. Comparison of Master Rank to IO Factor and *BRC* Factor (Cramer M7.7)

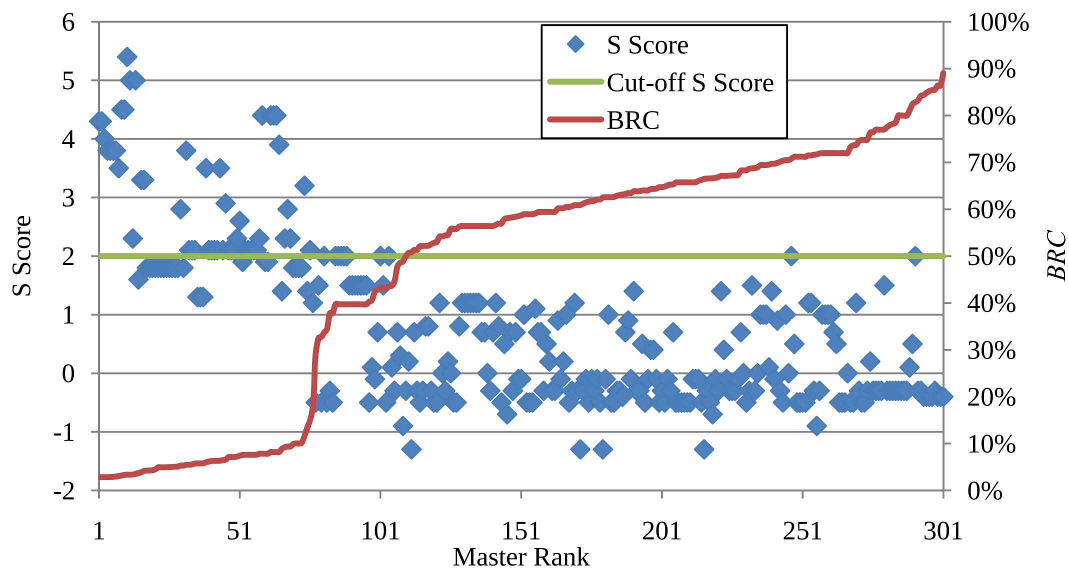


Figure 3-9. Comparison of Master Rank to S Score and *BRC* Factor (Cramer M7.7)

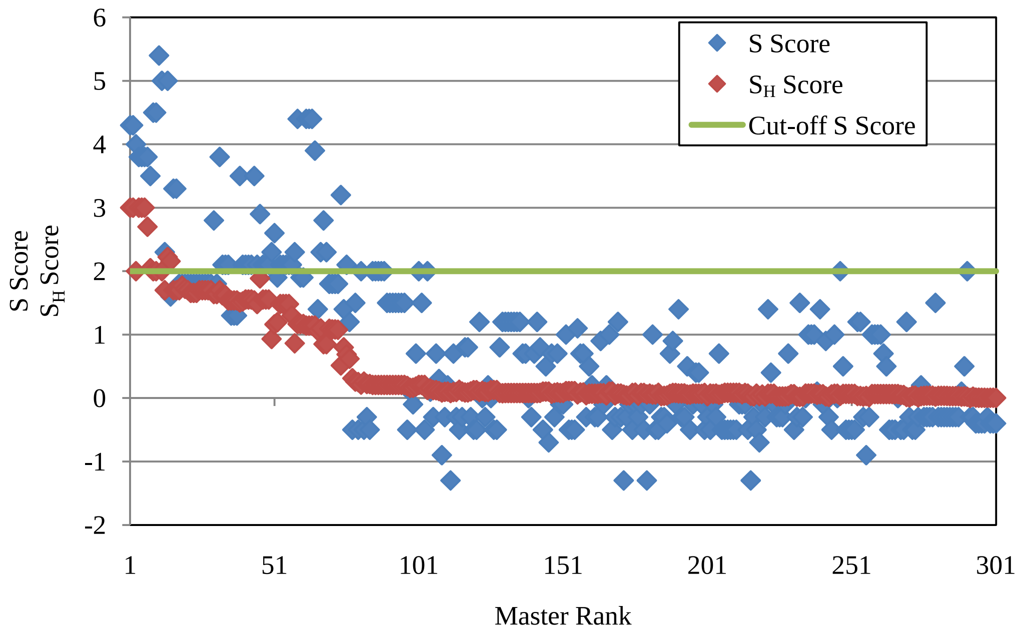


Figure 3-10. Comparison Master Rank to S Score to S_H Score (Cramer M7.7)

The null hypotheses for the construction date time periods (pre-1931, 1931-1950, 1951-1970, 1971-1990, and 1991-2010) are given as:

H_o for *BRC*:

> There is no statistically significant difference between the mean *BRC* factors based on Cramer's ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for IO:

> There is no statistically significant difference between the mean IO factors based on Cramer's ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S scores:

> There is no statistically significant difference between the mean scaled S scores based on Cramer's ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S_H scores:

> There is no statistically significant difference between the mean scaled S_H scores based on Cramer's ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

Table 3-25 summarizes the ANOVA tests for construction date time period.

Table 3-25. ANOVA Summary for Construction Dates (Cramer M7.7)

Factor	***P-value***	$\boldsymbol{F_{calc}}$	$\boldsymbol{F_{crit}}$	**Relationship**	**Rejection Statement**
BRC	7.92E-77	175.5	2.402	$F_{calc} > F_{crit}$	Reject H_o
IO	6.33E-93	246.7	2.402	$F_{calc} > F_{crit}$	Reject H_o
Scaled S Score	1.42E-40	67.85	2.402	$F_{calc} > F_{crit}$	Reject H_o
Scaled S_H	2.66E-88	225.1	2.402	$F_{calc} > F_{crit}$	Reject H_o

By rejecting the null hypotheses, it is concluded that at least one of the means is different from the others for the construction date time periods. The P-value is the actual probability of obtaining a test statistic at least as extreme as the one that was actually observed, when assuming the null hypothesis is true. The P-value is the actual probability that the null hypothesis should not be rejected. Therefore, it represents that for the construction date time periods; the null hypotheses will be rejected for essentially 100% of samples for a magnitude 7.7 earthquake based on Cramer's data. Tukey's Multiple Comparison Procedure will determine which categories are significantly different from the others. Table 3-26 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the *BRC* factors of the construction date time periods for a magnitude 7.7 earthquake based upon Cramer's data.

Table 3-26. Tukey Multiple Comparison for Construction Date *BRC* (Cramer M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1991-2010	0.082678	1	5 vs 4	0.009934	<	0.056467
1931-1950	0.442980	2	5 vs 3	0.059877	<	0.127151
Pre 1931	0.562691	3	5 vs 2	0.179588	>	0.100506
1971-1990	0.612634	4	5 vs 1	0.539890	>	0.063440
1951-1970	0.622568	5	4 vs 3	0.049943	<	0.125834
			4 vs 2	0.169654	<	0.098835
			4 vs 1	0.529956	>	0.060758
			3 vs 2	0.119711	<	0.150822
			3 vs 1	0.480013	>	0.129114
			2 vs 1	0.360303	>	0.102978

By applying Tukey's procedure to the construction date time period *BRC* data, it is concluded that the data corresponding to Counter 1 (1991-2010 time period) has a significantly lower mean *BRC* when compared to each of the other time periods individually. Also, the data corresponding to Counter 2 (1931-1950 time period) has a significantly lower mean *BRC* when compared to Counter 5 (1951-1970 time period).

Table 3-27 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the IO factors of the construction date time periods for a magnitude 7.7 earthquake based upon Cramer's data.

Table 3-27. Tukey Multiple Comparison for Construction Date IO (Cramer M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1951-1970	0.041644	1	5 vs 4	0.485226	>	0.106288
1971-1990	0.048396	2	5 vs 3	0.618403	>	0.133263
Pre 1931	0.080455	3	5 vs 2	0.650461	>	0.062711
1931-1950	0.213632	4	5 vs 1	0.657213	>	0.065479
1991-2010	0.698857	5	4 vs 3	0.133177	<	0.155669
			4 vs 2	0.165235	<	0.102011
			4 vs 1	0.171987	>	0.103736
			3 vs 2	0.032058	<	0.129878
			3 vs 1	0.038810	<	0.131237
			2 vs 1	0.006752	<	0.058281

Applying Tukey's procedure to the construction date time period IO data concludes that the data corresponding to Counter 5 (1991-2010 time period) has a significantly higher mean IO compared to each of the other time periods individually. This is consistent with the results from Table 3-26. Also, Counter 4 (1931-1950 time period) is significantly higher than Counter 1 (1951-1970 time period).

Table 3-28 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S_H scores of the construction date time periods for a magnitude 7.7 earthquake based upon Cramer's data.

Table 3-28. Tukey Multiple Comparison for Construction Date Scaled S_H Score (Cramer M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1951-1970	10.095063	1	5 vs 4	1.180368	<	0.103137
1971-1990	10.103332	2	5 vs 3	1.402683	<	0.129241
Pre 1931	10.167131	3	5 vs 2	1.466482	>	0.061028
1931-1950	10.389445	4	5 vs 1	1.474750	>	0.063698
1991-2010	11.569814	5	4 vs 3	0.222314	<	0.150822
			4 vs 2	0.286113	<	0.098835
			4 vs 1	0.294382	>	0.100506
			3 vs 2	0.063799	<	0.125834
			3 vs 1	0.072068	>	0.127151
			2 vs 1	0.008269	>	0.056467

Applying Tukey's procedure to the construction date time period scaled S_H score data concludes that the data corresponding to Counter 1 (1951-1970 time period) has a significantly lower mean scaled S_H score when compared to each of the other time periods individually. Also, Counter 2 (1971-1990 time period) has a significantly lower scaled S_H score than Counter 5 (1991-2010 time period).

All of these results are valid for approximately 95% of samples, when many samples are gathered. The results from Tukey's Multiple Comparison Test on the construction date time periods for the mean *BRC*, IO, and scaled S_H score for a magnitude 7.7 earthquake based upon Cramer's data seem to be consistent. The mean *BRC* is significantly lower for the 1991-2010 time period while the mean IO, and scaled S_H score is significantly higher for this same time period. This indicates that structures built in this time period tend to perform better than structures built in the other time periods. This makes sense because these are newer structures which have been designed based upon the more strict seismic provisions. Also, it appears that there is a significant difference between the mean *BRC* and mean IO for the 1931-1950 time period and the 1951-1970 time period.

The null hypotheses for the building type categories (concrete, pre-cast concrete, reinforced concrete, steel, unreinforced masonry, and wood) are given as:

H_o for *BRC*:

> There is no statistically significant difference between the mean *BRC* factors based on Cramer's ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for IO:

> There is no statistically significant difference between the mean IO factors based on Cramer's ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S scores:

> There is no statistically significant difference between the mean scaled S scores based on Cramer's ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S_H scores:

> There is no statistically significant difference between the mean scaled S_H scores based on Cramer's ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

Table 3-29 summarizes the ANOVA tests for building type categories.

Table 3-29. ANOVA Summary for Building Types (Cramer M7.7)

Factor	***P-value***	F_{calc}	F_{crit}	**Relationship**	**Rejection Statement**
BRC	2.24E-12	14.10	2.245	$F_{calc} > F_{crit}$	Reject H_o
IO	9.48E-09	9.881	2.245	$F_{calc} > F_{crit}$	Reject H_o
Scaled S Score	1.67E-15	17.91	2.245	$F_{calc} > F_{crit}$	Reject H_o
Scaled S_H	2.80E-08	9.347	2.245	$F_{calc} > F_{crit}$	Reject H_o

By rejecting the null hypotheses, it is concluded that at least one of the means is different from the others for the building type categories. Based upon the P-value, for the building type categories, the null hypotheses will be rejected for essentially 100% of samples for a magnitude 7.7 earthquake based on Cramer's data. Tukey's Multiple Comparison Procedure will determine which categories are significantly different from the others. Table 3-30 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the *BRC* factors of the building type categories for a magnitude 7.7 earthquake based upon Cramer's data.

Table 3-30. Tukey Multiple Comparison for Building Type *BRC* (Cramer M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
Wood	0.238276	1	6 vs 5	0.077045	<	0.289372
Steel	0.430845	2	6 vs 4	0.113965	<	0.316304
RM	0.542357	3	6 vs 3	0.124155	<	0.305530
URM	0.552546	4	6 vs 2	0.235667	<	0.287919
Concrete	0.589467	5	6 vs 1	0.428236	>	0.301170
PC	0.666512	6	5 vs 4	0.036921	<	0.162990
			5 vs 3	0.047110	<	0.140947
			5 vs 2	0.158622	>	0.097028
			5 vs 1	0.351191	>	0.131227
			4 vs 3	0.010190	<	0.190206
			4 vs 2	0.121701	<	0.160396
			4 vs 1	0.314270	>	0.183119
			3 vs 2	0.111512	<	0.137939
			3 vs 1	0.304081	>	0.163808
			2 vs 1	0.192569	>	0.127990

Applying Tukey's procedure to the building type category *BRC* data concludes that the data corresponding to Counter 1 (Wood) has a significantly lower mean *BRC* compared to each of the other building types individually. The data corresponding to Counter 2 (Steel) has a significantly lower *BRC* mean compared to Counter 5 (Concrete).

Table 3-31 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the IO factors of the building type categories for a magnitude 7.7 earthquake based upon Cramer's data.

Table 3-31. Tukey Multiple Comparison for Building Type IO (Cramer M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
PC	0.023167	1	6 vs 5	0.117842	<	0.154294
URM	0.072818	2	6 vs 4	0.191489	<	0.197472
Concrete	0.082196	3	6 vs 3	0.319856	>	0.158195
RM	0.210563	4	6 vs 2	0.329233	>	0.220752
Steel	0.284209	5	6 vs 1	0.378885	>	0.363063
Wood	0.402051	6	5 vs 4	0.073647	<	0.166286
			5 vs 3	0.202013	>	0.116969
			5 vs 2	0.211391	>	0.193358
			5 vs 1	0.261042	<	0.347089
			4 vs 3	0.128367	<	0.169913
			4 vs 2	0.137744	<	0.229295
			4 vs 1	0.187396	<	0.368320
			3 vs 2	0.009377	<	0.196486
			3 vs 1	0.059029	<	0.348841
			2 vs 1	0.049652	<	0.381308

Applying Tukey's procedure to the building type category IO data concludes that the data corresponding to Counter 6 (Wood) has a significantly higher mean IO compared to PC, URM, and Concrete. The data corresponding to Counter 5 (Steel) has a significantly higher mean IO compared to URM and Concrete.

Table 3-32 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S_H scores of the building types for a magnitude 7.7 earthquake based upon Cramer's data.

Table 3-32. Tukey Multiple Comparison for Building Type Scaled S_H Score (Cramer M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
PC	10.056310	1	6 vs 5	0.335186	<	0.351041
URM	10.120438	2	6 vs 4	0.478119	>	0.449278
Concrete	10.200747	3	6 vs 3	0.734224	>	0.359917
RM	10.456852	4	6 vs 2	0.814532	>	0.502244
Steel	10.599784	5	6 vs 1	0.878660	>	0.826022
Wood	10.934971	6	5 vs 4	0.142933	<	0.378326
			5 vs 3	0.399038	>	0.266121
			5 vs 2	0.479346	>	0.439919
			5 vs 1	0.543474	<	0.789679
			4 vs 3	0.256105	<	0.386576
			4 vs 2	0.336413	<	0.521680
			4 vs 1	0.400541	<	0.837982
			3 vs 2	0.080308	<	0.447034
			3 vs 1	0.144436	<	0.793664
			2 vs 1	0.064128	<	0.867532

Tukey's procedure for the building type category scaled S_H score data concludes that the data corresponding to Counter 6 (Wood) has a significantly higher scaled mean S_H score compared to each of the other building types, except Steel. Also, Table 3-32 shows that the data corresponding to Counter 5 (Steel) has a significantly higher mean scaled S_H score compared to URM and PC.

All of these results are valid for approximately 95% of samples, when many samples are gathered. The results from Tukey's Multiple Comparison Test on the building type categories for the mean *BRC*, IO, and scaled S_H score for a magnitude 7.7 earthquake based upon Cramer's data seem to be fairly consistent. The mean *BRC* is significantly lower for Wood structures. Steel and Wood structures tend to have the significantly highest mean IO, and scaled S_H score when compared to most other building type categories. It should be noted that Tukey's Multiple Comparison Test was performed on the scaled S scores one time since the S scores do not change for the three earthquake scenarios and was included with the Cramer, magnitude 6.5 data.

Figure 3-11 depicts a potential application to emergency management. It can be seen that there are several structures that have high *BRC* factors. For emergency planning, structures with lower *BRC* factors should be considered as primary locations for shelters.

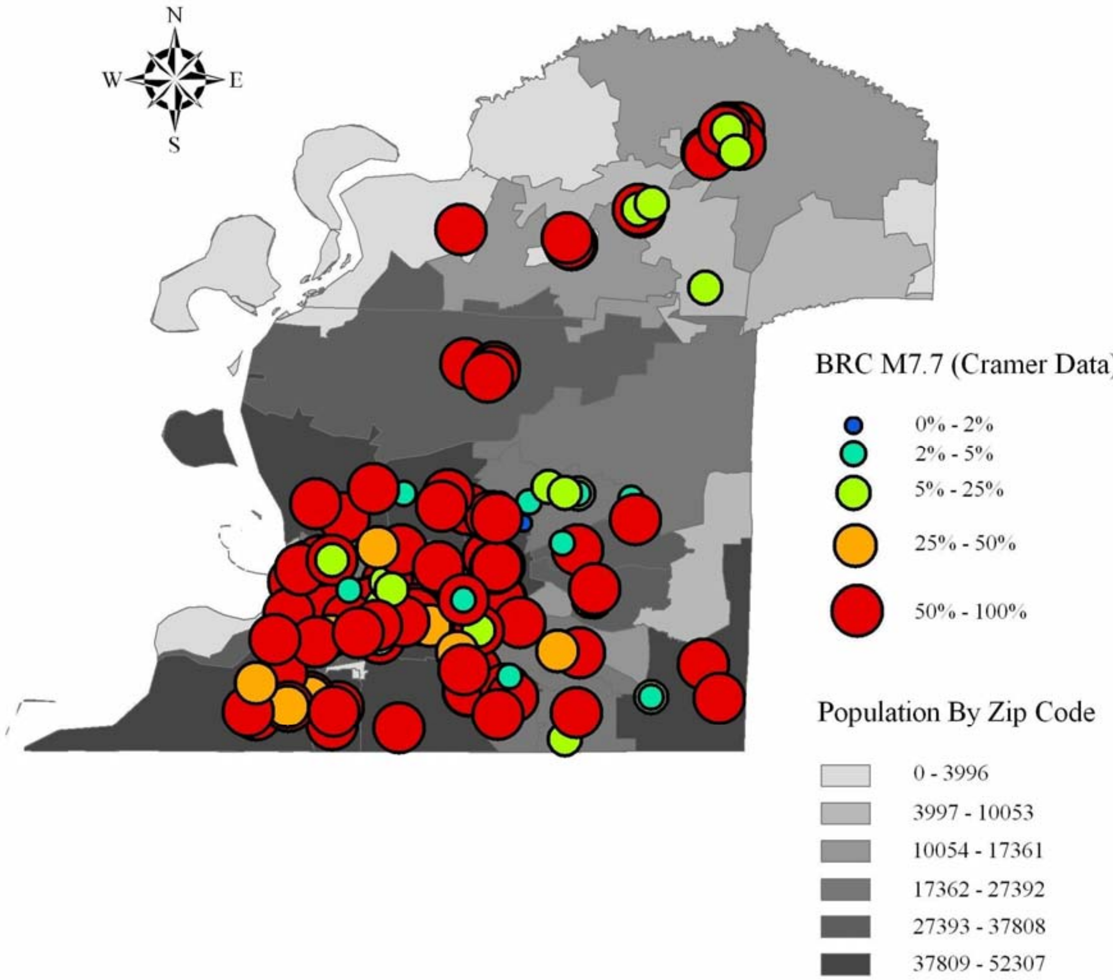


Figure 3-11. Population Distribution of *BRC* Factors (Cramer M7.7)

3.2.8 Magnitude 7.7 (USGS Data)

For this scenario, the USGS ground motion maps for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone (Cottonwood Grove Fault) were imported into HAZUS. Figure 3-12 shows the trend of the *BRC* factor increasing as the IO decreases. Figure 3-13 depicts the *BRC* factor increasing as the S scores decrease. However, it can be seen that the *BRC* values tend to be smaller than those calculated using Cramer's data maps. Figure 3-14 shows the relationship between the S scores and the S_H scores. It can be seen from this plot that the RVS procedure predicts about the same number of S scores above the cut-off score as compared with the number of S_H scores calculated from HAZUS-MH-MR3. Table 3-33 summarizes the means and medians of S scores and S_H scores. Based upon the plots and summary tables for this scenario; the RVS procedure seems to not be conservative. That is, the RVS procedure produced a higher mean S score as compared to the HAZUS-S_H score. This means that the RVS procedure produced higher S scores for some structures while HAZUS produced lower S_H scores for the same structures.

Table 3-33. Mean and Median (USGS M7.7)

	S Score	**S_H Score**	**S Score (≥ 2.0)**	**S_H Score (≥ 2.0)**	**S Score (< 2.0)**	**S_H Score (< 2.0)**
Mean	0.8	1.0	2.9	2.8	0.3	0.8
Median	0.5	0.7	2.3	3.0	-0.1	0.4

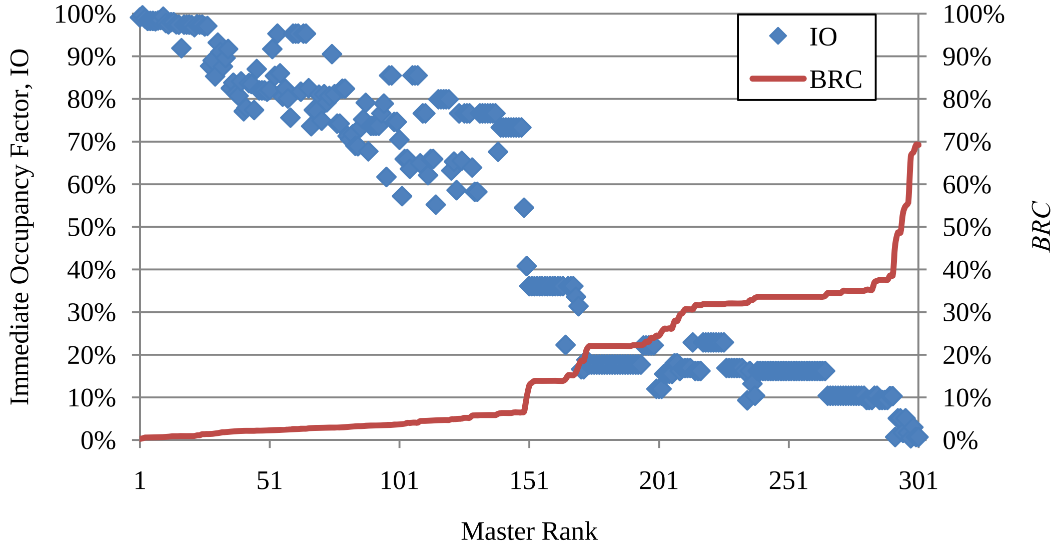


Figure 3-12. Comparison of Master Rank to IO Factor and *BRC* Factor (USGS M7.7)

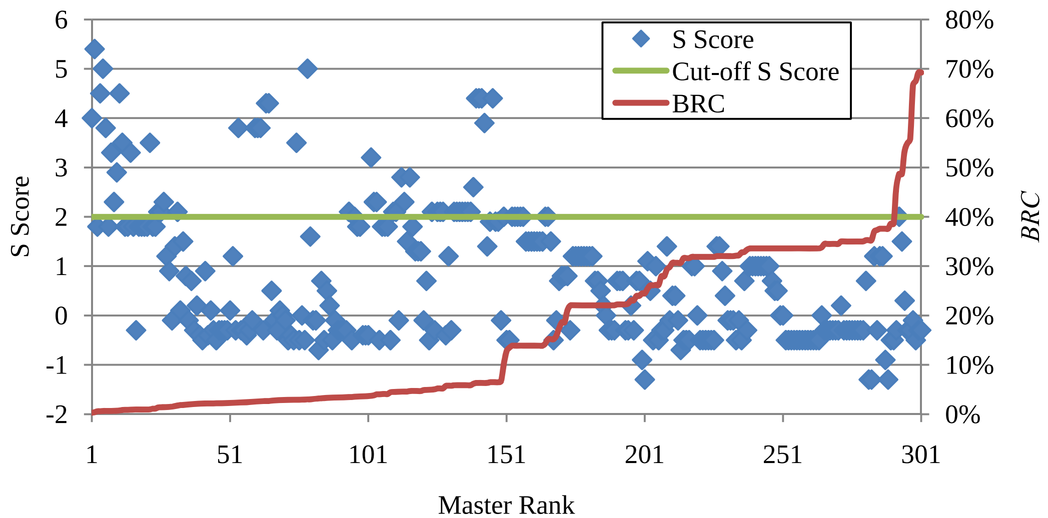


Figure 3-13. Comparison of Master Rank to S Score and *BRC* Factor (USGS M7.7)

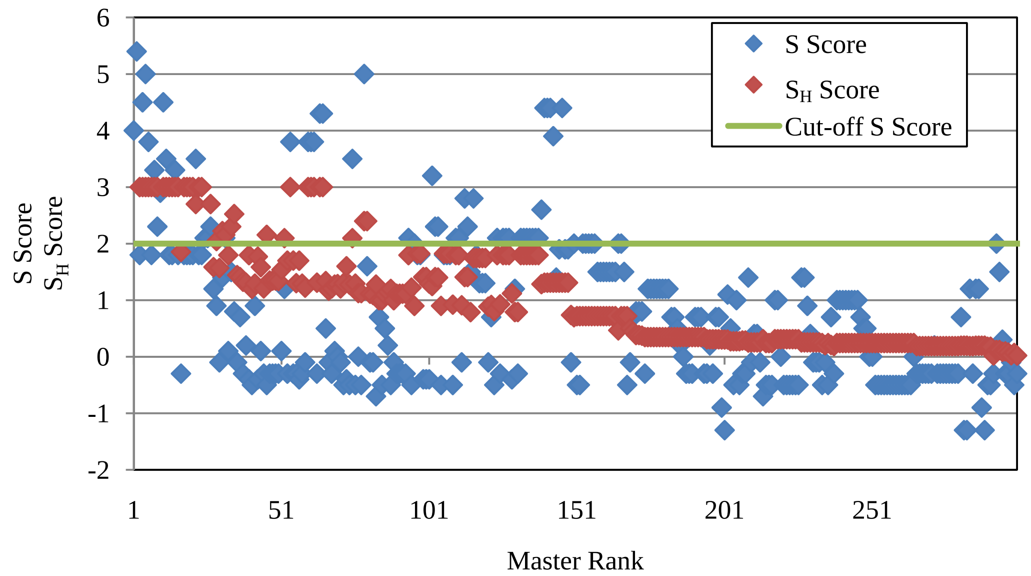


Figure 3-14. Comparison Master Rank to S Score to S_H Score (USGS M7.7)

The null hypotheses for the construction date time periods (pre-1931, 1931-1950, 1951-1970, 1971-1990, and 1991-2010) are given as:

H_o for *BRC*:

> There is no statistically significant difference between the mean *BRC* factors based on USGS ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for IO:

> There is no statistically significant difference between the mean IO factors based on USGS ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S scores:

> There is no statistically significant difference between the mean scaled S scores based on USGS ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S_H scores:

> There is no statistically significant difference between the mean scaled S_H scores based on USGS ground motion data, for the construction date time periods, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

Table 3-34 summarizes the ANOVA tests for construction date time period.

Table 3-34. ANOVA Summary for Construction Dates (USGS M7.7)

Factor	*P-value*	F_{calc}	F_{crit}	Relationship	Rejection Statement
BRC	1.86E-20	29.18	2.402	$F_{calc} > F_{crit}$	Reject H_o
IO	3.32E-32	50.16	2.402	$F_{calc} > F_{crit}$	Reject H_o
Scaled S Score	1.42E-40	67.85	2.402	$F_{calc} > F_{crit}$	Reject H_o
Scaled S_H	5.14E-52	96.12	2.402	$F_{calc} > F_{crit}$	Reject H_o

By rejecting the null hypotheses, it is concluded that at least one of the means is different from the others for the construction date time periods. Based upon the P-value, for the building type categories, the null hypotheses will be rejected for essentially 100% of samples for a magnitude 7.7 earthquake based on USGS data. Tukey's Multiple Comparison Procedure will determine which categories are significantly different from the others. Table 3-35 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the *BRC* factors of the construction date time periods for a magnitude 7.7 earthquake based upon USGS data.

Table 3-35. Tukey Multiple Comparison for Construction Date *BRC* (USGS M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
1991-2010	0.033956	1	5 vs 4	0.113038	<	0.114647
1931-1950	0.175074	2	5 vs 3	0.172105	>	0.113460
1971-1990	0.175517	3	5 vs 2	0.172548	>	0.135990
1951-1970	0.234584	4	5 vs 1	0.313667	>	0.116417
Pre 1931	0.347622	5	4 vs 3	0.059067	>	0.050914
			4 vs 2	0.059510	<	0.090622
			4 vs 1	0.200629	>	0.057202
			3 vs 2	0.000443	<	0.089116
			3 vs 1	0.141562	>	0.054783
			2 vs 1	0.141119	>	0.092852

By applying Tukey's procedure to the construction date time period *BRC* data, it is concluded that the data corresponding to Counter 1 (1991-2010 time period) has a significantly lower mean *BRC* compared to each of the other time periods individually. Also, the data corresponding to Counter 5 (Pre-1931 time period) is significantly different from data corresponding to Counter 2 and Counter 3. Data corresponding to Counter 4 is significantly different from data corresponding to Counter 3. These unexpected inconsistencies are most likely due to low number of ground motion parameters in the USGS ground motion data.

Table 3-36 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the IO factors of the construction date time periods for a magnitude 7.7 earthquake based upon USGS data.

Table 3-36. Tukey Multiple Comparison for Construction Date IO (USGS M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
Pre 1931	0.171909	1	5 vs 4	0.371391	>	0.182764
1951-1970	0.304667	2	5 vs 3	0.401754	>	0.107833
1971-1990	0.447532	3	5 vs 2	0.544619	>	0.112593
1931-1950	0.477895	4	5 vs 1	0.677377	>	0.229149
1991-2010	0.849286	5	4 vs 3	0.030363	<	0.175410
			4 vs 2	0.173228	<	0.178376
			4 vs 1	0.305986	>	0.267675
			3 vs 2	0.142865	>	0.100216
			3 vs 1	0.275622	>	0.223328
			2 vs 1	0.132758	<	0.225665

Applying Tukey's procedure to the construction date time period IO data concludes that the data corresponding to Counter 5 (1991-2010 time period) has a significantly higher mean IO compared to each of the other time periods individually. Also, other significant differences can be seen in the lower portion of the table. As with the *BRC*, these may be attributed to the lack of variety of ground motion values with the USGS data.

Table 3-37 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S_H scores of the construction date time periods for a magnitude 7.7 earthquake based upon USGS data.

Table 3-37. Tukey Multiple Comparison for Construction Date Scaled S_H Score (USGS M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
Pre 1931	10.320644	1	5 vs 4	1.323807	>	0.409746
1951-1970	10.528751	2	5 vs 3	1.448412	>	0.245384
1971-1990	10.767668	3	5 vs 2	1.687329	>	0.255739
1931-1950	10.892273	4	5 vs 1	1.895435	>	0.512227
1991-2010	12.216080	5	4 vs 3	0.124604	<	0.390069
			4 vs 2	0.363521	<	0.396665
			4 vs 1	0.571628	<	0.595245
			3 vs 2	0.238917	>	0.222856
			3 vs 1	0.447024	<	0.496627
			2 vs 1	0.208107	<	0.501824

Applying Tukey's procedure to the construction date time period scaled S_H score data concludes that the data corresponding to Counter 5 (1991-2010 time period) has a significantly higher mean scaled S_H score when compared to each of the other time periods individually. Also, Counter 2 (1951-1970 time period) has a significantly lower mean scaled S_H score than Counter 3 (1971-1990 time period).

All of these results are valid for approximately 95% of samples, when many samples are gathered. The results from Tukey's Multiple Comparison Test on the construction date time periods for the mean *BRC*, IO, and scaled S_H score for a magnitude 7.7 earthquake based upon USGS data seem to be fairly consistent. There seems to be some unexpected significant difference between certain time periods that was not observed with the analysis of the Cramer output. The mean *BRC* is significantly higher for the Pre-1931 time period while the mean IO, and scaled S_H score is significantly higher for the 1991-2010 time period. This indicates that structures built in the post-benchmark time period (1991-2010 time period) tend to perform better than structures built in the other time periods. Structures build in the Pre-1931 time period tend to perform poorly when compared to the other time periods. This makes sense because these are newer structures which have been designed based upon the more strict seismic provisions.

The null hypotheses for the building type categories (concrete, pre-cast concrete, reinforced concrete, steel, unreinforced masonry, and wood) are given as:

H_o for *BRC*:

> There is no statistically significant difference between the mean *BRC* factors based on USGS ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for IO:

> There is no statistically significant difference between the mean IO factors based on USGS ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S scores:

> There is no statistically significant difference between the mean scaled S scores based on USGS ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

H_o for scaled S_H scores:

> There is no statistically significant difference between the mean scaled S_H scores based on USGS ground motion data, for the building type categories, for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone.

Table 3-38 summarizes the ANOVA tests for building type categories.

Table 3-38. ANOVA Summary for Building Types (USGS M7.7)

Factor	***P-value***	F_{calc}	F_{crit}	**Relationship**	**Rejection Statement**
BRC	4.99E-09	10.20	2.245	$F_{calc} > F_{crit}$	Reject H_o
IO	1.86E-13	15.40	2.245	$F_{calc} > F_{crit}$	Reject H_o
Scaled S Score	1.67E-15	17.91	2.245	$F_{calc} > F_{crit}$	Reject H_o
Scaled S_H	1.44E-12	14.36	2.245	$F_{calc} > F_{crit}$	Reject H_o

By rejecting the null hypotheses, it is concluded that at least one of the means is different from the others for the building type categories. Based upon the P-value, for the building type categories, the null hypotheses will be rejected for essentially 100% of samples for a magnitude 7.7 earthquake based on Cramer's data. Tukey's Multiple Comparison Procedure will determine which categories are significantly different from the others. Table 3-39 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the *BRC* factors of the building type categories for a magnitude 7.7 earthquake based upon USGS data.

Table 3-39. Tukey Multiple Comparison for Building Type *BRC* (USGS M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
RM	0.079677	1	6 vs 5	0.027235	<	0.172450
Wood	0.082680	2	6 vs 4	0.035348	<	0.097133
Steel	0.151904	3	6 vs 3	0.086259	>	0.057824
URM	0.202815	4	6 vs 2	0.155483	>	0.078204
PC	0.210928	5	6 vs 1	0.158486	>	0.083996
Concrete	0.238163	6	5 vs 4	0.008113	<	0.188500
			5 vs 3	0.059024	<	0.171584
			5 vs 2	0.128249	<	0.179481
			5 vs 1	0.131251	<	0.182079
			4 vs 3	0.050911	<	0.095587
			4 vs 2	0.120135	>	0.109129
			4 vs 1	0.123138	>	0.113352
			3 vs 2	0.069224	<	0.076275
			3 vs 1	0.072227	<	0.082204
			2 vs 1	0.003002	<	0.097621

Applying Tukey's procedure to the building type category *BRC* data concludes that the data corresponding to Counter 6 (Concrete) has a significantly higher mean *BRC* when compared to RM, Wood, and Steel. The data corresponding to Counter 4 (URM) has a significantly higher mean *BRC* compared to RM and Wood.

Table 3-40 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the IO factors of the building type categories for a magnitude 7.7 earthquake based upon USGS data.

Table 3-40. Tukey Multiple Comparison for Building Type IO (USGS M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
Concrete	0.287185	1	6 vs 5	0.058792	<	0.203285
PC	0.359167	2	6 vs 4	0.133443	<	0.171182
URM	0.425955	3	6 vs 3	0.273170	>	0.236045
Steel	0.565682	4	6 vs 2	0.339958	<	0.379162
Wood	0.640333	5	6 vs 1	0.411940	>	0.174915
RM	0.699125	6	5 vs 4	0.074652	<	0.158836
			5 vs 3	0.214379	<	0.227251
			5 vs 2	0.281167	<	0.373751
			5 vs 1	0.353149	>	0.162852
			4 vs 3	0.139727	<	0.199051
			4 vs 2	0.206515	<	0.357307
			4 vs 1	0.278497	>	0.120412
			3 vs 2	0.066788	<	0.392533
			3 vs 1	0.138770	<	0.202270
			2 vs 1	0.071982	<	0.359110

Applying Tukey's procedure to the building type category IO data concludes that the data corresponding to Counter 1 (Concrete) has a significantly lower mean IO compared to Steel, Wood, and RM. The data corresponding to Counter 5 (Wood) has a significantly higher mean IO compared Concrete.

Table 3-41 shows a summary of the results of Tukey's Multiple Comparison Procedure applied to the scaled S_H scores of the building types for a magnitude 7.7 earthquake based upon USGS data.

Table 3-41. Tukey Multiple Comparison for Building Type Scaled S_H Score (USGS M7.7)

Groups	Average	Counter	Comparison	Difference		Rejection Region
PC	10.510259	1	6 vs 5	0.089759	<	0.545724
Concrete	10.516319	2	6 vs 4	0.171047	<	0.426944
URM	10.656483	3	6 vs 3	0.784280	>	0.603412
Steel	11.269716	4	6 vs 2	0.924445	>	0.436315
RM	11.351004	5	6 vs 1	0.930504	<	0.986410
Wood	11.440763	6	5 vs 4	0.081288	<	0.456683
			5 vs 3	0.694521	>	0.624807
			5 vs 2	0.834686	>	0.465455
			5 vs 1	0.840745	<	0.999642
			4 vs 3	0.613233	>	0.524262
			4 vs 2	0.753398	>	0.317987
			4 vs 1	0.759457	<	0.940080
			3 vs 2	0.140164	<	0.531921
			3 vs 1	0.146224	<	1.032267
			2 vs 1	0.006060	<	0.944373

Tukey's procedure for the building type category scaled S_H score data concludes that the data corresponding to Steel, RM, and Wood has a significantly higher mean scaled S_H score compared to PC and Concrete.

All of these results are valid for approximately 95% of samples, when many samples are gathered. The mean *BRC* is significantly higher for Concrete structures. Concrete tends to have the significantly lowest mean IO. Steel RM and Wood structures tend to have the significantly highest scaled S_H score. It should be noted that Tukey's Multiple Comparison Test was performed on the scaled S scores one time since the S scores do not change for the three earthquake scenarios and was included with the Cramer, magnitude 6.5 data.

It should be noted that the results do not definitively state that one population group is always significantly greater or less than the other population groups. For example, with the USGS data, Table 3-39 shows that data corresponding to Concrete structures has a significantly higher mean *BRC* when compared to RM, Wood, and Steel. However, Table 3-41 shows that the data corresponding to Steel, RM, and Wood structures has a significantly higher mean scaled S_H score compared to PC and Concrete, but does not show that the Concrete structure data has a significantly lower mean scaled S_H score. These differences are likely due to some of the ambiguities and assumptions involved in the collection of building data. This can be misleading and requires careful attention when interpreting the tabular results.

Figure 3-15 depicts a potential application to emergency management. It can be seen that there are several structures that have high *BRC* factors, but not as many as with the Cramer 7.7 data. This shows that for Cramer's site-specific data, more structures with high *BRC* factors are seen. For emergency planning, structures with lower *BRC* factors should be considered as primary locations for shelters.

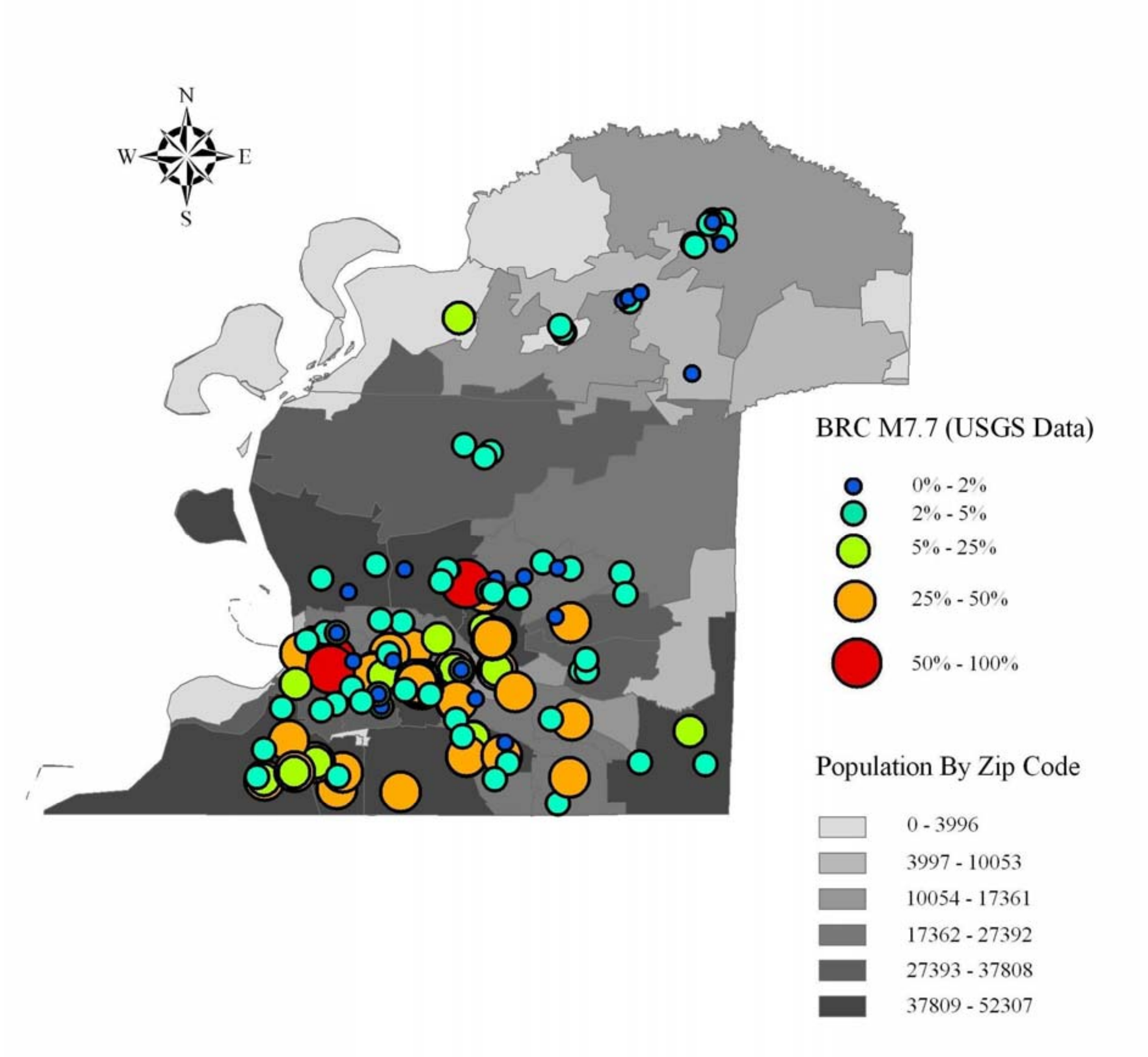


Figure 3-15. Population Distribution of *BRC* Factors (USGS M7.7)

3.2.9 Comparison of the Magnitude 7.7 Scenarios

One of the objectives of this research is to determine how site-specific ground motion data compares with the standard USGS ground motion. The site-specific ground motion data used in this research is the ground motion maps generated by Cramer (Cramer, C.H., J.S. Gomberg, E.S. Scheig, B. A. Waldron, and K. Tucker 2004). First, a simple ANOVA test was performed on the two data sets for *BRC* values, IO values and S_H scores. The null hypothesis states, that there is no statistically significant difference between the mean *BRC* factor (mean IO factor and mean S_H score) based on Cramer's ground motion data and the mean *BRC* factor (mean IO factor and mean S_H score) based on the USGS ground motion data in Shelby County and Tipton County for a magnitude 7.7 earthquake on the southwest arm of the New Madrid seismic zone. Tukey's Multiple Comparison Procedure is not necessary here since only two data sets are being analyzed. Table 3-42 and Table 3-43 list the means and medians of the HAZUS-MH MR3 results using Cramer's data and USGS data, respectively. Table 3-44 shows a summary of the ANOVA analysis. The master rank for the magnitude 7.7 earthquake based upon Cramer's ground motion data is compared to the master rank for the magnitude 7.7 earthquake based upon the USGS ground motion data. Corresponding structures between the two data sets were matched and the difference between the master rank of the USGS data and Cramer data was computed. Figure 3-16 shows the comparison between the Cramer *BRC* factors and USGS *BRC* factors by structure. This plot was generated by matching corresponding structures from the Cramer *BRC* data with the USGS *BRC* data, and plotting the *BRC* data against the Cramer master rank. It can be seen that for each individual structure, the Cramer *BRC* factors are almost always higher than the USGS *BRC* factors when comparing the same structure in each data set, with the exception of a few outliers. The high number of unique ground motion parameters with the Cramer data produces more unique results which can greatly affect the *BRC* factors. High master rank structures are those which have low *BRC* factors and would tend to perform well during a magnitude 7.7 earthquake. It should be noted that for Figure 3-16, corresponding structures are being compared. A similar analysis was performed on the S_H scores. Corresponding structures were matched between the two data sets and their respective S_H scores were subtracted; (USGS S_H score minus Cramer S_H score). This was done to observe the differences between the HAZUS-generated scores (S_H score) for the two magnitude 7.7 scenarios, and plotting against the Cramer master rank. Since the differences in S_H scores is being observed, the USGS master rank could have been used as the horizontal axis and would have yielded the exact same result. All S_H scores that were calculated as infinite were given a score of 10. Figure 3-17 depicts the S_H score difference plot. It can be seen that the differences in S_H scores is less than 2.0 for most of the structures with the exception of a few outliers. Most structures fall within a difference of 2.0 for the S_H score. This means that a large difference in master rank does not necessarily denote a large difference in S_H score. This is most likely because the *BRC* factor is composed of all of the probability damage states output from HAZUS multiplied by building cost ratios; whereas the S_H score is only composed of the extensive and complete damage states. However, statistically there is a significant difference between mean *BRC* factors, IO factors, and S_H scores for the two magnitude 7.7 scenarios.

Table 3-42. Mean and Median for Cramer Magnitude 7.7

	***BRC* Factor**	**IO Factor**	**S_H Score**	**S_H Score (≥ 2.0)**	**S_H Score (< 2.0)**
Mean	47.98%	20.92%	0.5	2.5	0.4
Median	58.67	3.300	0.1	0.2	0.1

Table 3-43. Mean and Median for USGS Magnitude 7.7

	***BRC* Factor**	**IO Factor**	**S_H Score**	**S_H Score (≥ 2.0)**	**S_H Score (< 2.0)**
Mean	16.65%	49.01%	1.0	2.8	0.8
Median	12.78	36.10	0.7	3.0	0.4

Table 3-44. ANOVA Summary for Magnitude 7.7 Scenarios

Factor	***P-value***	**F_{calc}**	**F_{crit}**	**Relationship**	**Rejection Statement**
BRC	1.33E-56	312.5	3.857	$F_{calc} > F_{crit}$	Reject H_o
IO	1.59E-24	114.2	3.857	$F_{calc} > F_{crit}$	Reject H_o
S_H	2.61E-11	46.17	3.875	$F_{calc} > F_{crit}$	Reject H_o

The P-value represents that for the *BRC* factor, IO factor and S_H score, the null hypotheses will be rejected for essentially 100% of samples for a magnitude 7.7 earthquake comparing Cramer's data with USGS data.

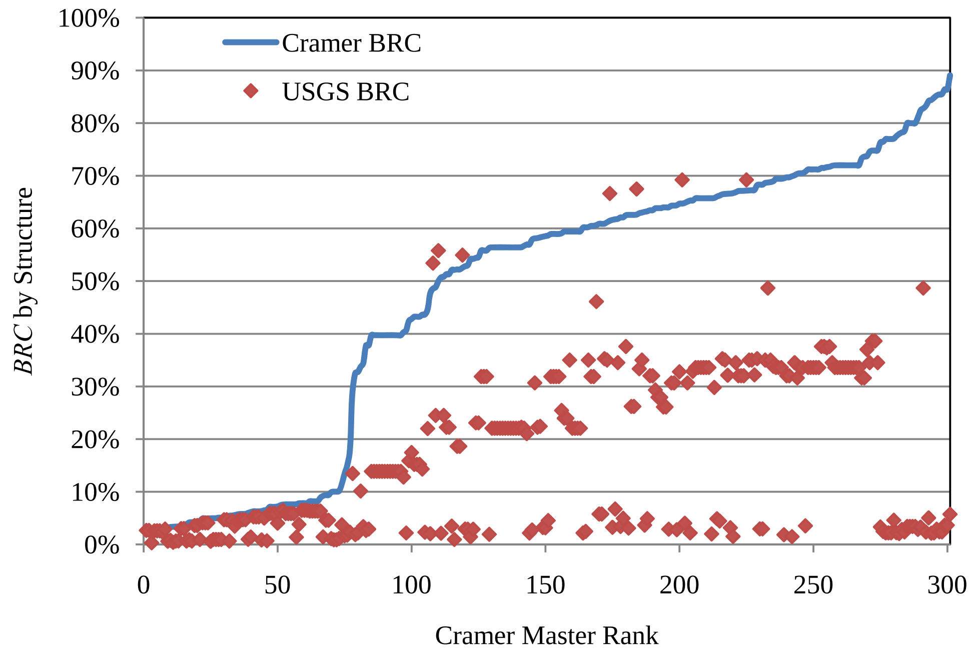


Figure 3-16. *BRC* by Structure vs. Cramer Master Rank

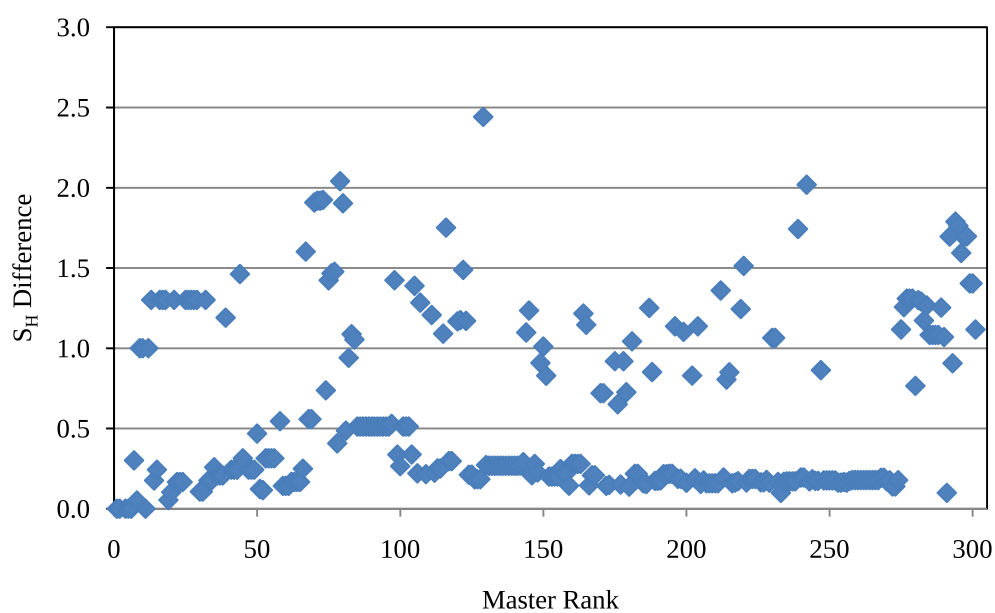


Figure 3-17. S_H Score Difference Plot

4 SUMMARY AND CONCLUSIONS

4.1 Summary

A structural assessment of buildings in Shelby County and Tipton County, Tennessee was conducted using the FEMA developed RVS procedure. The RVS procedure scores buildings based on their expected performance during an earthquake. The S score, from the RVS, is compared to an established cut-off score to determine if a building will be "safe to risk of life" or if a "detailed evaluation of the building is required." The building data collected during the RVS procedure was then input into the database management program InCAST, which maps the building data into HAZUS-MH MR3. The damage estimates are based on three earthquake scenarios. Two of the scenarios utilize customized ground motion maps developed for the mid-south region of the United States. The third scenario utilizes standard USGS ground motion maps. The scenario earthquakes are a magnitude 7.7 on the southwest arm of the New Madrid seismic zone (Cottonwood Grove fault), utilizing Cramer's ground motion maps, a magnitude 7.7 on the southwest arm of the New Madrid seismic zone (Cottonwood Grove fault), utilizing Cramer's USGS ground motion maps, and a magnitude 6.5 on the southern end of the southwest arm at Marked Tree, Arkansas, utilizing customized ground motion maps. The damage estimates are given in the form of probabilities for five damage states: none, slight, moderate, extensive, and complete. The damage states were used to compute three measures of loss: an Immediate Occupancy (IO) factor, a Building Replacement Cost (*BRC*) factor, and a S_H score. A structure prioritization was assembled based on the *BRC* and IO factors and the RVS S score. A statistical analysis was performed on the S score, *BRC* factor, IO factor, and S_H score for the three scenarios using analysis of variance to determine trends in the data and to make formal conclusions about how Cramer's data maps compared to the standardized USGS maps for a magnitude 7.7 earthquake, how the RVS procedure compared to the HAZUS output, and how building types and construction dates affected structure performance.

4.2 Conclusions

The first objective of this research was to prioritize the 301 structures based upon the HAZUS output and the S score. This prioritization has a direct application to mass population shelters which could potentially be used in the event of a natural disaster. This study used three factors to establish a shelter prioritization: the *BRC* factor, IO factor, and S score. The S score was established using the RVS procedure, where as the IO and *BRC* factors were calculated from HAZUS damage estimates. Unless building plans are available, the RVS procedure can be very subjective. Also, limiting the building type to one of the 15 options shown on the RVS data collection form can introduce a certain level of ambiguity since most buildings are a combination of building types. Uncertainties or how one assigns building irregularities can greatly affect a structure's S score. However, the RVS procedure is a cost effective method and quick measure of screening the seismic vulnerability of building structures. Figure 3-7, Figure 3-11, and Figure 3-15 show the prioritization of the 301 structures as a point coverage underlain by a population distribution of Shelby County and Tipton County.

HAZUS is capable of doing sophisticated calculations useful in estimating building performance. Since this study was performed as a Level 2 HAZUS-MH MR3 analysis, no fragility curves were developed for individual buildings; rather, default fragility curves were assigned based upon building type. Thus, the HAZUS-MH MR3 output indicates approximate damage that can be expected for classes of building types. Once again, as a cost effective and efficient measure of estimating a buildings performance, HAZUS provides sophisticated loss estimates.

The second objective of this study was to make a formal conclusion as to how well the RVS procedure performs in identifying structures which may be seismically at risk as compared to the HAZUS-MH MR3 output. For the magnitude 6.5 scenario (based upon Cramer's ground motion maps), the RVS procedure seems to be conservative when compared to the HAZUS analysis output. This statement can be further generalized in saying that for relatively low magnitude earthquakes (6.5 and lower), the RVS procedure is a conservative, cost effective method for screening the seismic vulnerability of building structures and may be performed by an average person who is under time constraints, or lacks knowledge of HAZUS. For the magnitude 7.7 scenario (based upon Cramer's ground motion maps), the RVS procedure seems un-conservative when compared to the HAZUS-MH MR3 analysis output. This statement can be further generalized in saying that for higher magnitude earthquakes (above 6.5), the RVS procedure may not produce a conservative assessment of the seismic vulnerability of building structures and a more sophisticated loss estimate analysis may be necessary to accurately identify structures at risk. For the magnitude 7.7 scenario (based upon standard USGS ground motion maps), the RVS procedure seems un-conservative when compared to the HAZUS analysis output. However, the RVS procedure seems to be comparable to the HAZUS-MH MR3 output. This statement can be further generalized in saying that for higher magnitude earthquakes (above 6.5), the RVS procedure may not produce a conservative assessment of the seismic vulnerability of building structures and a more sophisticated loss estimate analysis may be necessary to accurately identify structures at risk. Overall, the RVS procedure seems to produce a conservative assessment for magnitude 6.5 earthquakes; however, for magnitude earthquakes higher than 6.5, HAZUS-MH MR3 seems to produce a conservative assessment.

The third objective of this study was to make formal statements about building type and construction time period as they affect the HAZUS output and S score. For all three magnitude scenarios, based upon the RVS procedure and the HAZUS-MH MR3 output; unreinforced masonry structures tend to perform the worst when compared to the other building type categories. Wood structures, followed by steel structures tend to perform the best. Structures built in the 1991-2010 time period (post-benchmark) tend to perform much better than those built pre-1991.

The fourth objective of this study was to make a formal conclusion as to how site-specific ground motion maps compare with those provided by the USGS with respect to the HAZUS-MH MR3 output. Comparing the site-specific ground motion maps developed by Cramer to the standardized USGS ground motion maps, overall structure performance is lower with the site-specific ground motion data. It was seen in Figure 3-16 and Figure 3-17 that the *BRC* factors for the Cramer data are almost always higher than the *BRC* factors for the USGS data for corresponding structures. This may indicate that the USGS maps give a fair representation for large regional studies; however, Cramer's maps are better for localized studies on smaller areas. Overall, this shows that the Cramer site-specific ground motion maps are a more appropriate representation of structure performance, for this data set.

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APPENDIX A: HAZUS-MH MR3 Building Type Definitions

Descriptions of the 15 model building types as shown on the RVS data collection form and utilized within HAZUS-MH MR3 are listed below (HAZUS-MH MR3 Technical Manual Section 5.2.1 2006a).

Wood, Light Frame (W1):

These are typically single-family or small, multiple-family dwellings of not more than 5,000 square feet of floor area. The essential structural feature of these buildings is repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small. These buildings may have relatively heavy masonry chimneys and may be partially or fully covered with masonry veneer. Most of these buildings, especially the single-family residences, are not engineered but constructed in accordance with "conventional construction" provisions of building codes. Hence, they usually have the components of a lateral-force-resisting system even though it may be incomplete. Lateral loads are transferred by diaphragms to shear walls. The diaphragms are roof panels and floors that may be sheathed with sawn lumber, plywood or fiberboard sheathing. Shear walls are sheathed with boards, stucco, plaster, plywood, gypsum board, particle board, or fiberboard, or interior partition walls sheathed with plaster or gypsum board.

Wood, Greater than 5,000 Sq. Ft. (W2):

These buildings are typically commercial or industrial buildings, or multi-family residential buildings with a floor area greater than 5,000 square feet. These buildings include structural systems framed by beams or major horizontally spanning members over columns. These horizontal members may be glue-laminated (glu-lam) wood, solid-sawn wood beams, or wood trusses, or steel beams or trusses. Lateral loads usually are resisted by wood diaphragms and exterior walls sheathed with plywood, stucco, plaster, or other paneling. The walls may have diagonal rod bracing. Large openings for stores and garages often require post-and-beam framing. Lateral load resistance on those lines may be achieved with steel rigid frames (moment frames) or diagonal bracing.

Steel Moment Frame (S1):

These buildings have a frame of steel columns and beams. In some cases, the beam-column connections have very small moment resisting capacity but, in other cases, some of the beams and columns are fully developed as moment frames to resist lateral forces. Usually the structure is concealed on the outside by exterior nonstructural walls, which can be of almost any material (curtain walls, brick masonry, or precast concrete panels), and on the inside by ceilings and column furring. Diaphragms transfer lateral loads to moment-resisting frames. The diaphragms can be almost any material. The frames develop their stiffness by full or partial moment connections. The frames can be located almost anywhere in the building. Usually the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction. Steel moment frame buildings are typically more flexible than shear wall buildings. This low stiffness can result in large inter-story drifts that may lead to relatively greater nonstructural damage.

Steel Braced Frame (S2):

These buildings are similar to steel moment frame buildings except that the vertical components of the lateral-force-resisting system are braced frames rather than moment frames.

Steel Light Frame (S3):

These buildings are pre-engineered and prefabricated with transverse rigid frames. The roof and walls consist of lightweight panels, usually corrugated metal. The frames are designed for maximum efficiency, often with tapered beam and column sections built up of light steel plates. The frames are built in segments and assembled in the field with bolted joints. Lateral loads in the transverse direction are resisted by the rigid frames with loads distributed to them by diaphragm elements, typically rod-braced steel roof framing bays. Tension rod bracing typically resists loads in the longitudinal direction.

Steel Frame with Cast-In-Place Concrete Shear Walls (S4):

The shear walls in these buildings are cast-in-place concrete and may be bearing walls. The steel frame is designed for vertical loads only. Diaphragms of almost any material transfer lateral loads to the shear walls. The steel frame may provide a secondary lateral-force-resisting system depending on the stiffness of the frame and the moment capacity of the beam-column connections. In modern “dual” systems, the steel moment frames are designed to work together with the concrete shear walls.

Steel Frame with Unreinforced Masonry Infill Walls (S5):

This is one of the older types of buildings. The infill walls usually are offset from the exterior frame members, wrap around them, and present a smooth masonry exterior with no indication of the frame. Solidly infilled masonry panels, when they fully engage the surrounding frame members (i.e. lie in the same plane), may provide stiffness and lateral load resistance to the structure.

Reinforced Concrete Moment Resisting Frames (C1):

These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There are a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes leading to partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behavior and are likely to undergo large deformations during an earthquake without brittle failure of frame members and collapse.

Concrete Shear Walls (C2):

The vertical components of the lateral-force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive and the wall stresses are low but reinforcing is light. In newer buildings, the shear walls often are limited in extent, generating concerns about boundary members and overturning forces.

Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3):
These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behavior of the system.

Precast Concrete Tilt-Up Walls (PC1):
These buildings have a wood or metal deck roof diaphragm, which often is very large, that distributes lateral forces to precast concrete shear walls. The walls are thin but relatively heavy while the roofs are relatively light. Older or non-seismic-code buildings often have inadequate connections for anchorage of the walls to the roof for out-of-plane forces, and the panel connections often are brittle. Tilt-up buildings usually are one or two stories in height. Walls can have numerous openings for doors and windows of such size that the wall looks more like a frame than a shear wall.

Precast Concrete Frames with Concrete Shear Walls (PC2):
These buildings contain floor and roof diaphragms typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. Precast concrete girders and columns support the diaphragms. The girders often bear on column corbels. Closure strips between precast floor elements and beam-column joints usually are cast-in-place concrete. Welded steel inserts often are used to interconnect precast elements. Precast or cast-in-place concrete shear walls resist lateral loads. For buildings with precast frames and concrete shear walls to perform well, the details used to connect the structural elements must have sufficient strength and displacement capacity; however, in some cases, the connection details between the precast elements have negligible ductility.

Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1):
These buildings have perimeter bearing walls of reinforced brick or concrete-block masonry. These walls are the vertical elements in the lateral-force-resisting system. The floors and roofs are framed with wood joists and beams either with plywood or braced sheathing, the latter either straight or diagonally sheathed, or with steel beams with metal deck with or without concrete fill. Interior wood posts or steel columns support wood floor framing; steel columns support steel beams.

Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2):
These buildings have bearing walls similar to those of reinforced masonry bearing wall structures with wood or metal deck diaphragms, but the roof and floors are composed of precast concrete elements such as planks or tee-beams and the precast roof and floor elements are supported on interior beams and columns of steel or concrete (cast-in-place or precast). The precast horizontal elements often have a cast-in-place topping.

Unreinforced Masonry Bearing Walls (URM):

These buildings include structural elements that vary depending on the building's age and, to a lesser extent, its geographic location. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood framing. In large multistory buildings, the floors are cast-in-place concrete supported by the unreinforced masonry walls and/or steel or concrete interior framing. In unreinforced masonry constructed after 1950 (outside California) wood floors usually have plywood rather than board sheathing. In regions of lower seismicity, buildings of this type constructed more recently can include floor and roof framing that consists of metal deck and concrete fill supported by steel framing elements. The perimeter walls, and possibly some interior walls, are unreinforced masonry. The walls may or may not be anchored to the diaphragms. Ties between the walls and diaphragms are more common for the bearing walls than for walls that are parallel to the floor framing. Roof ties usually are less common and more erratically spaced than those at the floor levels. Interior partitions that interconnect the floors and roof can reduce diaphragm displacements.

APPENDIX B: Procedure for Creating HAZUS-MH MR3-Compatible Ground Motion Maps

A step-by-step procedure was developed for converting ground motion point data into a HAZUS-MH MR3 compatible map using ArcGIS v. 9.2 (Boling, 2009).

The data supplied for this study was in text format with a grid spacing of 0.01 degrees. A sample of the supplied data is listed in Table B-1. For ground motion maps, the parameter value could be the spectral acceleration (Sa), peak ground velocity (PGV), or the peak ground acceleration (PGA). The process for generating HAZUS-MH MR3 compatible maps can be broken down into three steps: importing point data into ArcMap, creating a fishnet to represent a spatial grid, and joining the fishnet with the point data; the end result is a polygon shape file.

Table B-1. Sample of Data Supplied for Maps

LONG	LAT	PARAMVALUE
-90.49500	34.505	0.075
-90.48500	34.505	0.075
-90.47499	34.505	0.075
-90.46500	34.505	0.075
-90.45499	34.505	0.075
-90.44499	34.505	0.075
-90.43498	34.505	0.075

1. Importing Point Data to ArcMap

1.1. Start MS Excel and open the .txt file containing the point data.

- 1.1.1. Choose “delimited” and hit next.
- 1.1.2. Choose “space” and hit next.
- 1.1.3. Choose “general” and hit next.

1.2. Now insert a new column next to the data to contain an ID value. Add a series of values from 1 through the last line of data (in this case 1 to 15,625).

1.3. Name the columns: ID, LONG, LAT, and PARAMVALUE as shown in Figure B-1.

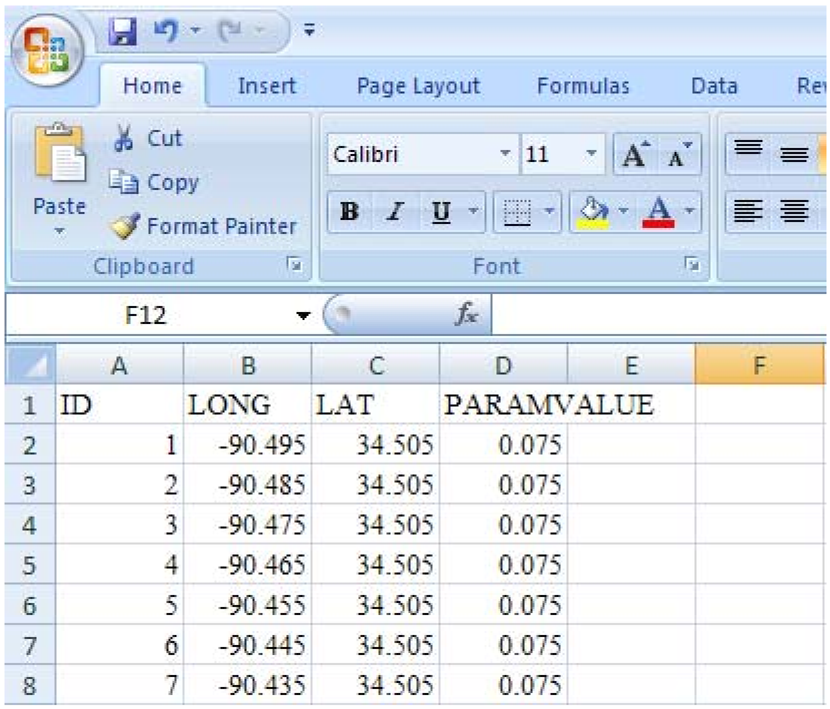

Figure B-1. Data as it should appear in MS Excel

1.4. Save the file as a .xls and close MS Excel.

1.5. Open ArcMap.

1.6. Click on the “Add Data” button, and browse to locate the .xls file. Double-click on the filename, and then select and add the file appended by the “$.” This file is the .xls table.

1.7. Right-click on the table added from Step 1.6 and click “Display XY Data.” A window, shown in Figure B-2 will prompt the user to select the mapping options for the table.

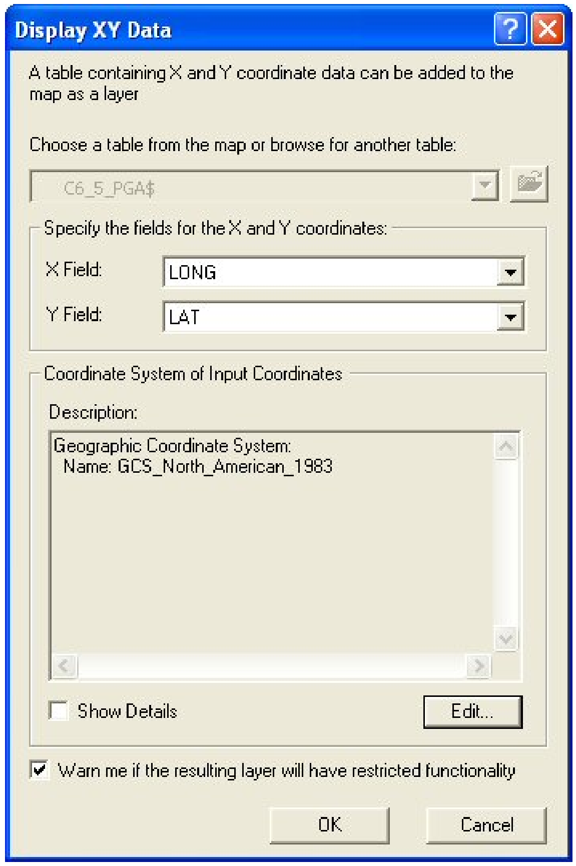

Figure B-2. XY Data Display Window

1.8. Specify the fields for the X and Y coordinates: X Field- Long, Y Field- Lat.

1.9. The map projection must now be assigned to the point data. Map projections are mathematical formulas that allow data obtained from a curved surface to be displayed on a flat surface (ESRI 2007). Click the Edit button located under the “Coordinate System of Input Coordinates” as shown in Figure B-2. The user will be prompted with a “Spatial Reference Properties” window.

1.9.1. In the Spatial Reference Properties window, click Select.

1.9.2. Browse for the North American Datum 1983.prj. The file is located in the Geographic Coordinate Systems, North America, North American Datum 1983.prj (this is the last projection of the North American projections). Click Add. Click Apply.

1.9.3. Close the Spatial Reference by clicking OK and then close the XY Display windows by clicking OK, (you may get a warning stating the table has no object ID field, ignore warning because this functionality will be available after Step 1.10). Click OK.

1.10. Right-click on the newly created "Event Theme." Scroll to "Data" and click "Export Data." The Export Data window will appear as shown in Figure B-3. This export will produce a shapefile of the .xls data (a shapefile is a geospatial vector data format). Click OK. A pop-up window will ask if the user would like to add the exported data to the map as a layer. Click yes. The point data has now been added to ArcMap in the proper format.

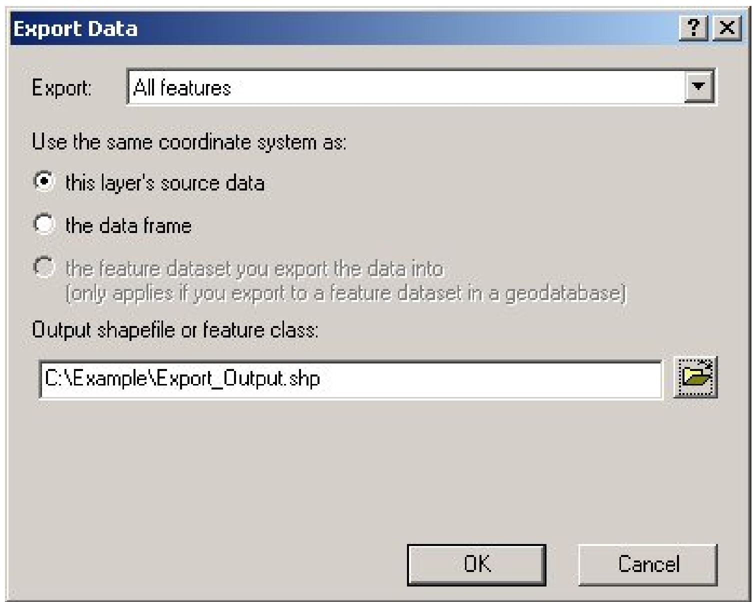

Figure B-3. Export Data Window

2. Creating a Fishnet

A fishnet is a "polygon coverage" which is a system of polygons covering a region. Maps for HAZUS-MH MR3 must be in polygon coverage format.

2.1. On the Windows desktop, click Start, All Programs, Accessories, Command Prompt.

2.2. At this point, the user will need to create a folder to hold the fishnet that is about to be built. This can be done by clicking Start, My Computer, Local Disk (C:), Right-click in the (C:) drive window, scroll to New, Folder. The folder can be named anything; however, for this example the folder will be called Example. If there is an existing workspace folder, it may be used; however, the user must have write access to the folder.

2.3. On the Windows Desktop, click Start, All Programs, Accessories, Command Prompt.

2.4. Type command: “cd C:\workspace” (or cd and the folder name created in Step 2.2) to obtain this prompt “C:\workspace>”

2.5. Type command: “ARC.”

2.6. Type command: “generate (create file name)” In this case the file will be called “example.” See Figure B-4 for a screen capture of the Command Prompt.

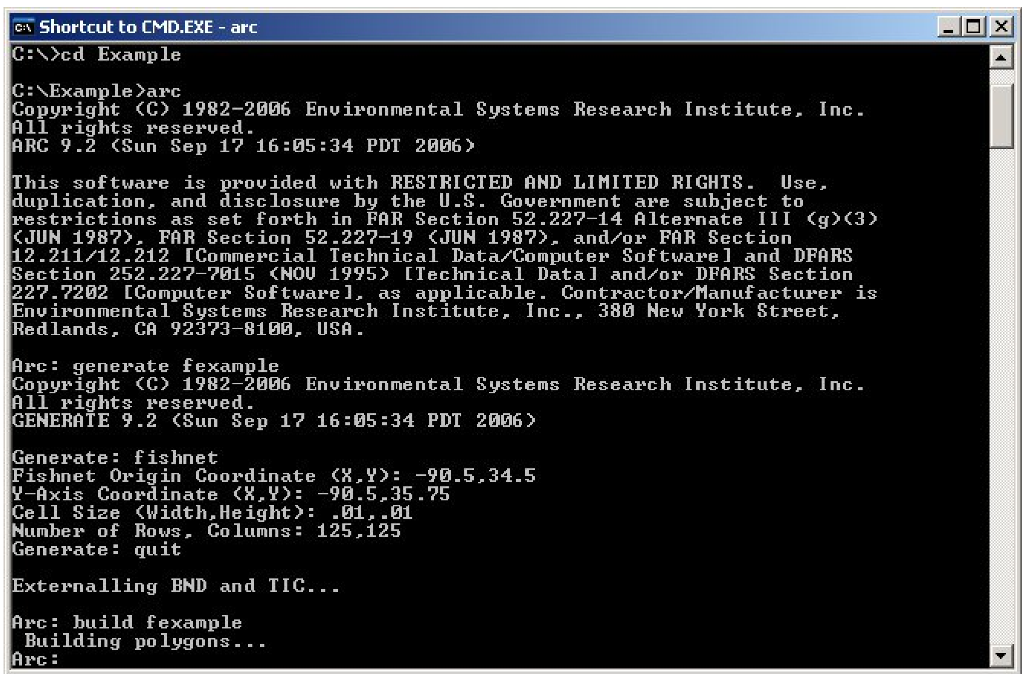

Figure B-4. Command Prompt for fishnet

2.7. Type command: “fishnet

The origin and other needed coordinates can be found by investigating the x,y points (latitude and longitude in ArcMap). To assure that the point is in the center of the fishnet you will need to add (or subtract depending on the geographic location) half of the cell size, or interval the data was provided in, to the coordinates. For this study, the fishnet origin was -90.5, 34.5; the Y-axis coordinate was -90.5, 35.75; the cell size was 0.01, 0.01, and the number of rows and columns was 125, 125.

2.8. Enter the origin of the fishnet: -90.5, 34.5

2.9. Enter the Y-axis coordinate: -90.5, 35.75

2.10. Enter the cell size: 0.01, 0.01

2.11. Enter the number of rows and columns: 125, 125

2.12. Type command: "quit"

2.13. Type command: "build (the file name created in Step 2.6)"

2.14. Type command: "quit" and close the command prompt window.

2.15. Click on the "Add Data" button in ArcMap and locate the file name created in Step 2.13 (the file will be located in the workspace folder), click Add. A warning stating that there is missing spatail reference information will appear. Ignore the warning and press OK as this will be assigned in Step 2.17.

2.16. Right-click the file added from step 2.15. Scroll to "Data," "Export Data." A pop-up window will ask if the user would like to add the exported data to the map as a layer, click yes.

2.17. The projection must now be defined for the fishnet. In the ArcToolbox window, find the "Data Management Tools;" this is located under "Projections and Transformations," click "Define Projection." Figure B-5 shows the Define Projection window. The "Input Data Set or Feature Class" is the file from Step 2.16 and the "Coordinate System" is the North American Datum 1983.prj. Click the box next to Coordinate System, and assign the North American Datum 1983.prj file. As before, it is located in the Geographic Coordinate Systems, North America, North American Datum 1983.prj (this is the last projection of the North American projections). Click Add.

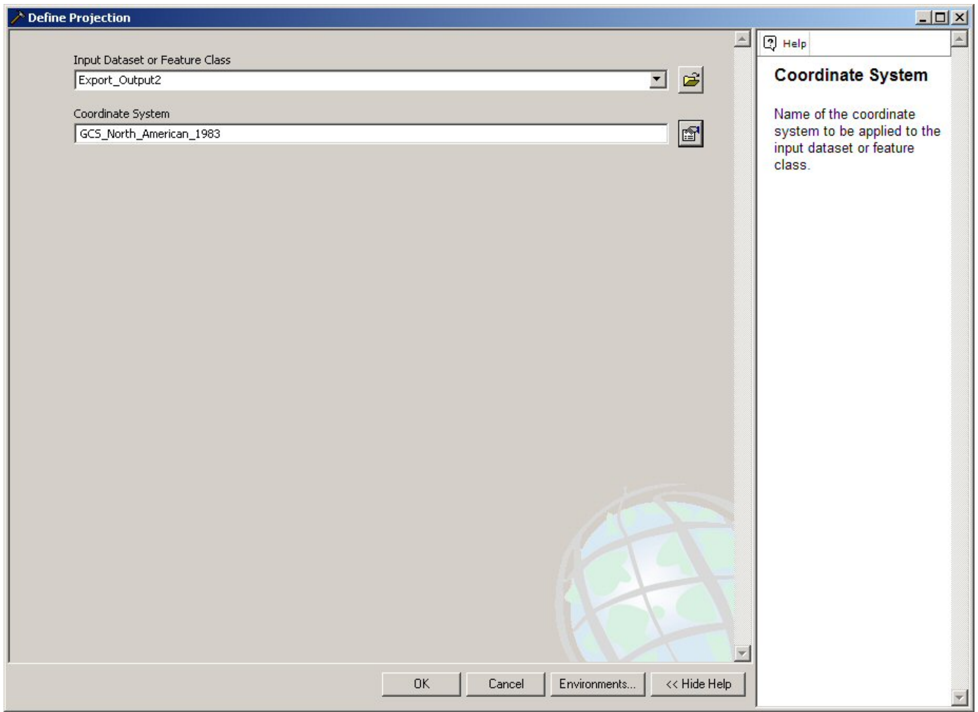

Figure B-5. Define Projection Window

3. Joining Point Data with the Fishnet

In order to assign parameter values to the fishnet created in Step 2, the fishnet must be joined with the point values from Step 1.

3.1. Right-click on the fishnet from Step 2.17, scroll to "Joins and Relates," and click "Join." Figure B-6 shows the Join Data window. Choose "Join data from another layer based on spatial location." The file for part 1 should be the shape file containing the point data. The radio button for "each polygon will be given all the attributes of the point…" should be selected for part 2. Select a location for the join shapefile in part 3, and click OK.

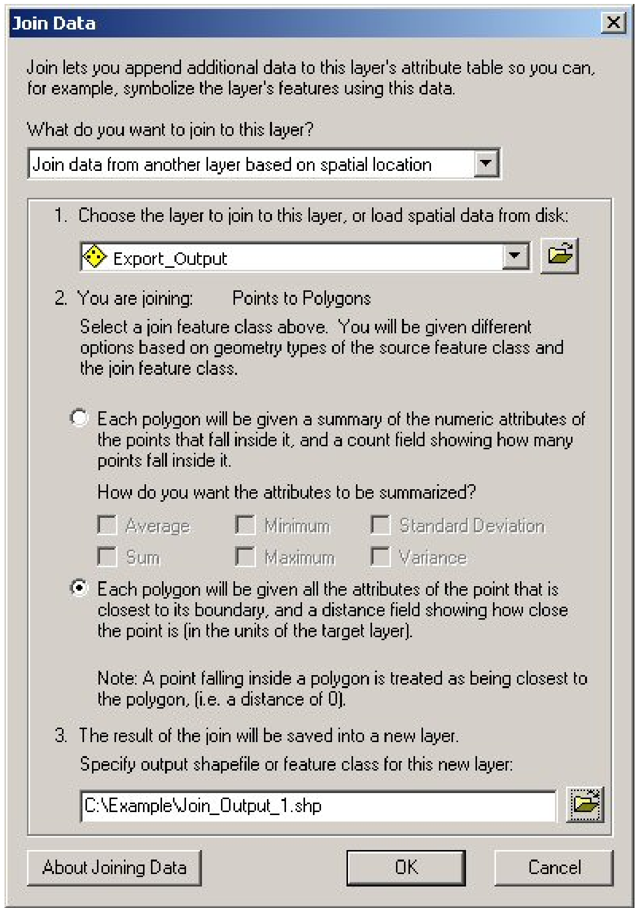

Figure B-6. Join Data Window

3.2. Find the "Dissolve" command in the Data Management Tools under "Generalization." The Dissolve function can also be found by searching for "Dissolve." Figure B-7 shows the Dissolve window. The input feature class is the join output from step 3.1. Dissolve the file with respect to PARAMVALUE. The Dissolve function combines polygons who share the same PARAMVALUE.

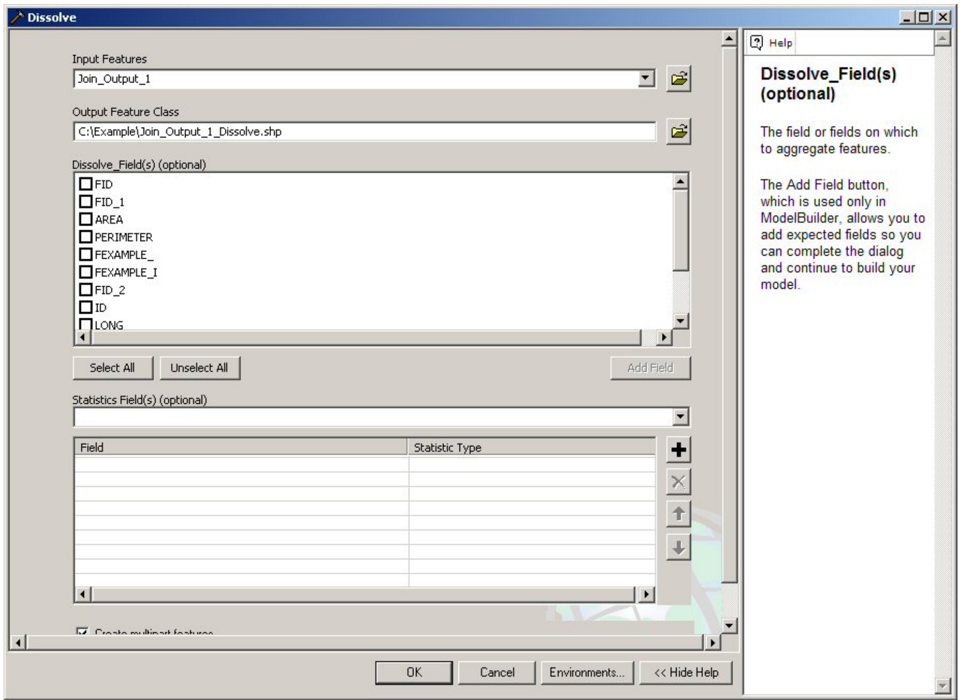

Figure B-7. Dissolve window

3.3. Open ArcCatalog.

3.4. In ArcCatalog, right-click and create a new “Personal Geodatabase.”

3.5. Find the dissolved file, right-click, scroll to “Export,” “To Geodatabase (single).” Figure B-8 shows the window for exporting shapefiles to a geodatabase. The “Input Features” is the dissolved file, the “Output Location” is the geodatabase, and the “Output Feature Class” is the name of the file as it will appear in the geodatabase.

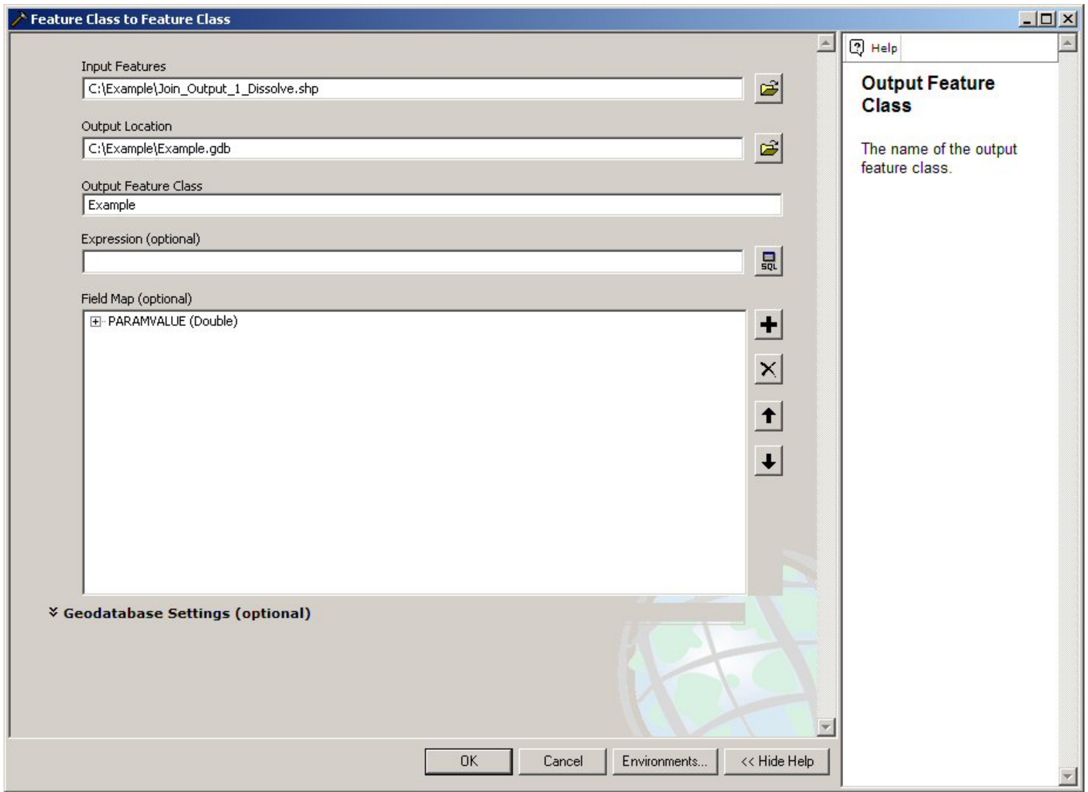

Figure B-8. Exporting to Geodatabase

APPENDIX C: Ground Motion Maps

The ground motion maps developed by Dr. Chris Cramer that were used in this study can be seen below along with USGS ground motion maps. The Cramer ground motion maps for the two earthquake scenarios, a magnitude 7.7 on the southwest arm of the New Madrid seismic zone (Cottonwood Grove fault) and a magnitude 6.5 on the southern end of the southwest arm at Marked Tree, Arkansas, are color coded to show the considerable number of unique ground motion values. The USGS ground motion maps for a magnitude 7.7 on the southwest arm of the New Madrid seismic zone (Cottonwood Grove Fault) show only a small number of unique ground motion values.

Table C-1. Ground Motion Map Summary

	Magnitude 6.5, Cramer Data	**Magnitude 7.7, Cramer Data**	**Magnitude 7.7, USGS Data**
0.3 s SA	C-1	C-5	C-9
1.0 s SA	C-2	C-6	C-10
PGV	C-3	C-7	C-11
PGA	C-4	C-8	C-12

Magnitude 6.5, Cramer Data

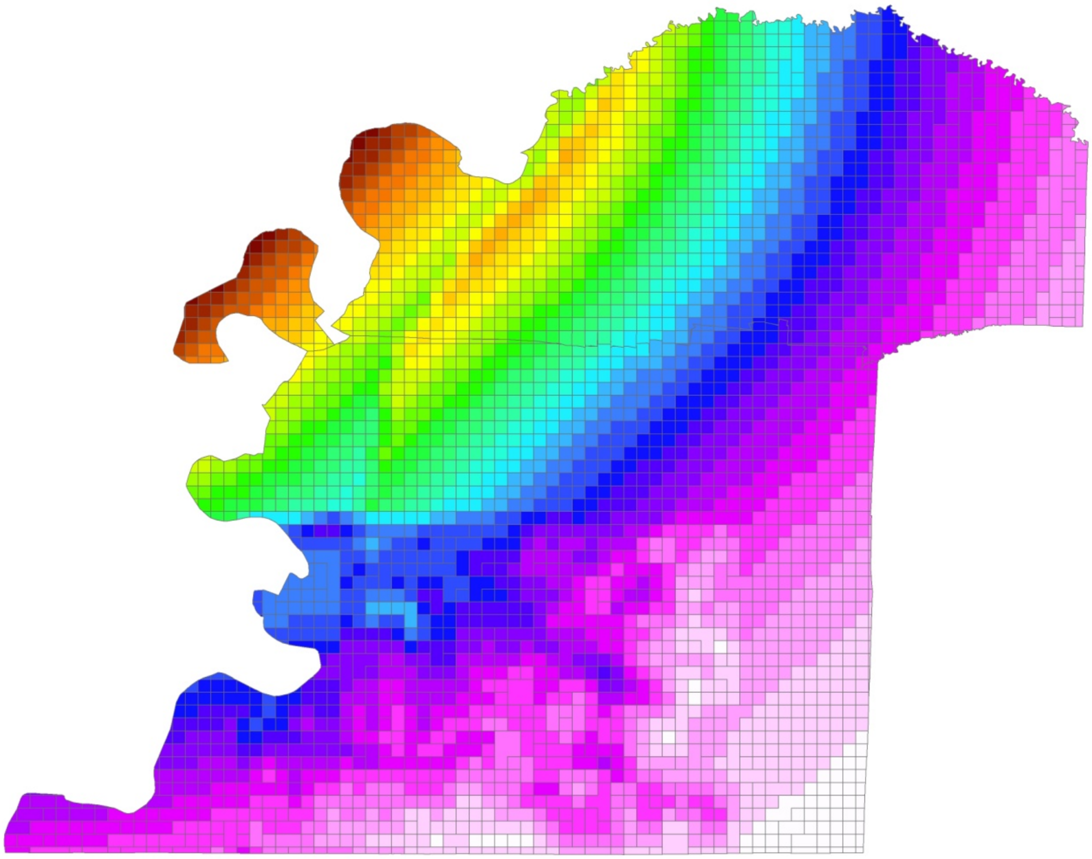

Figure C-1. 0.3 s SA, Magnitude 6.5 Range 0.190 – 0.512 g

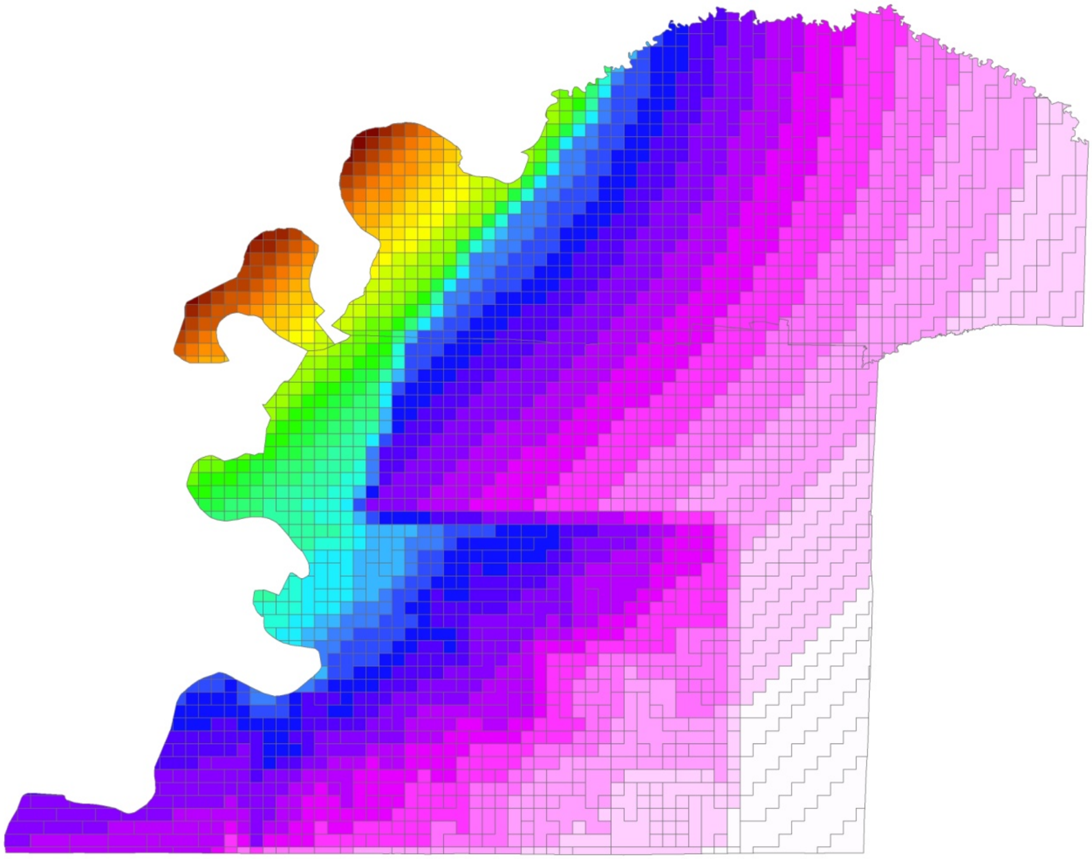

Figure C-2. 1.0 s SA, Magnitude 6.5 Range 0.064 – 0.304 g

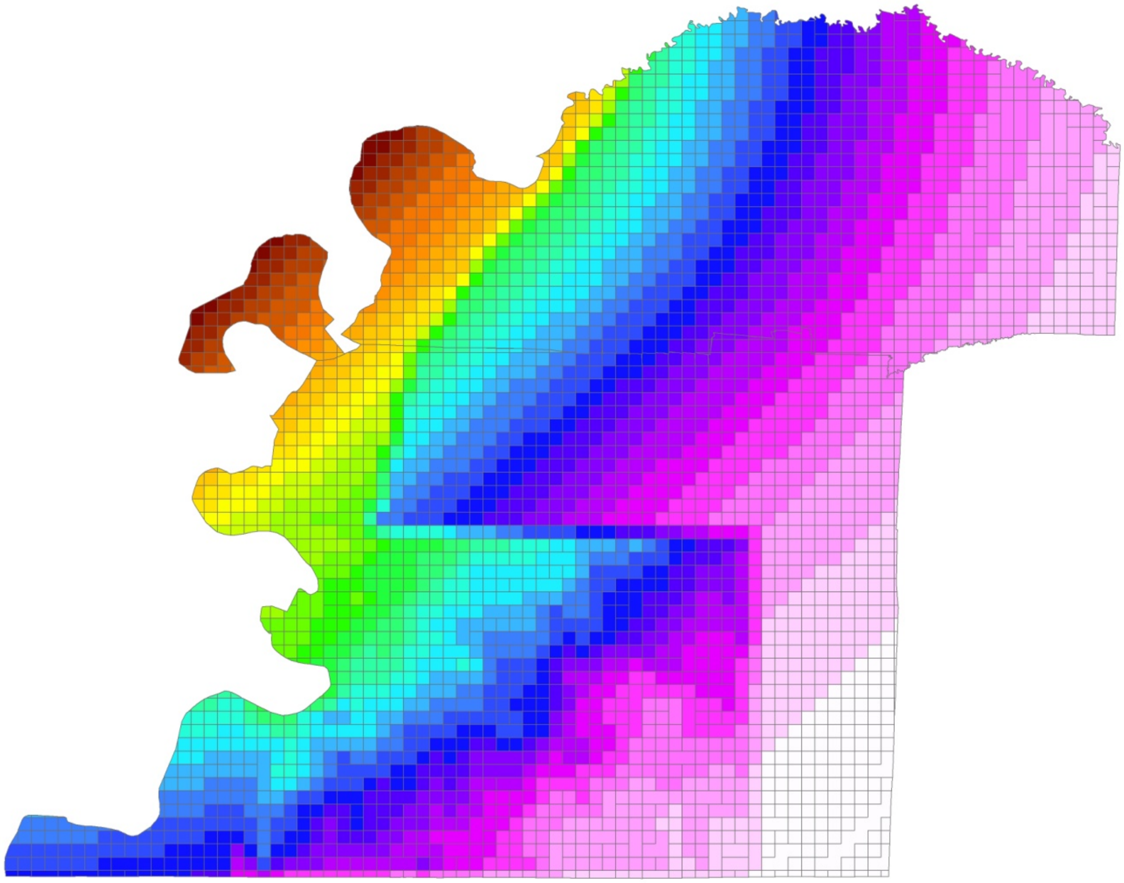

Figure C-3. PGV, Magnitude 6.5 Range 2.366 – 11.33 in/sec

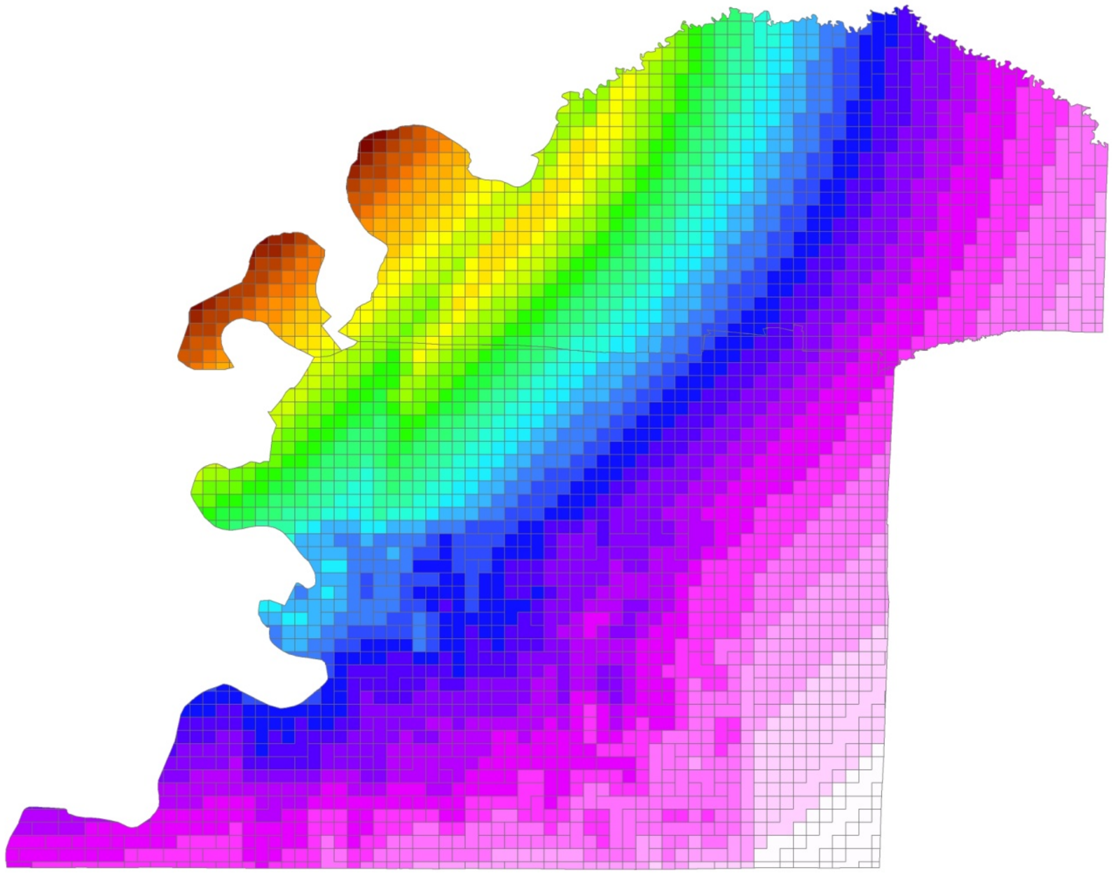

Figure C-4. PGA, Magnitude 6.5 Range 0.108 – 0.387 g

Magnitude 7.7, Cramer Data

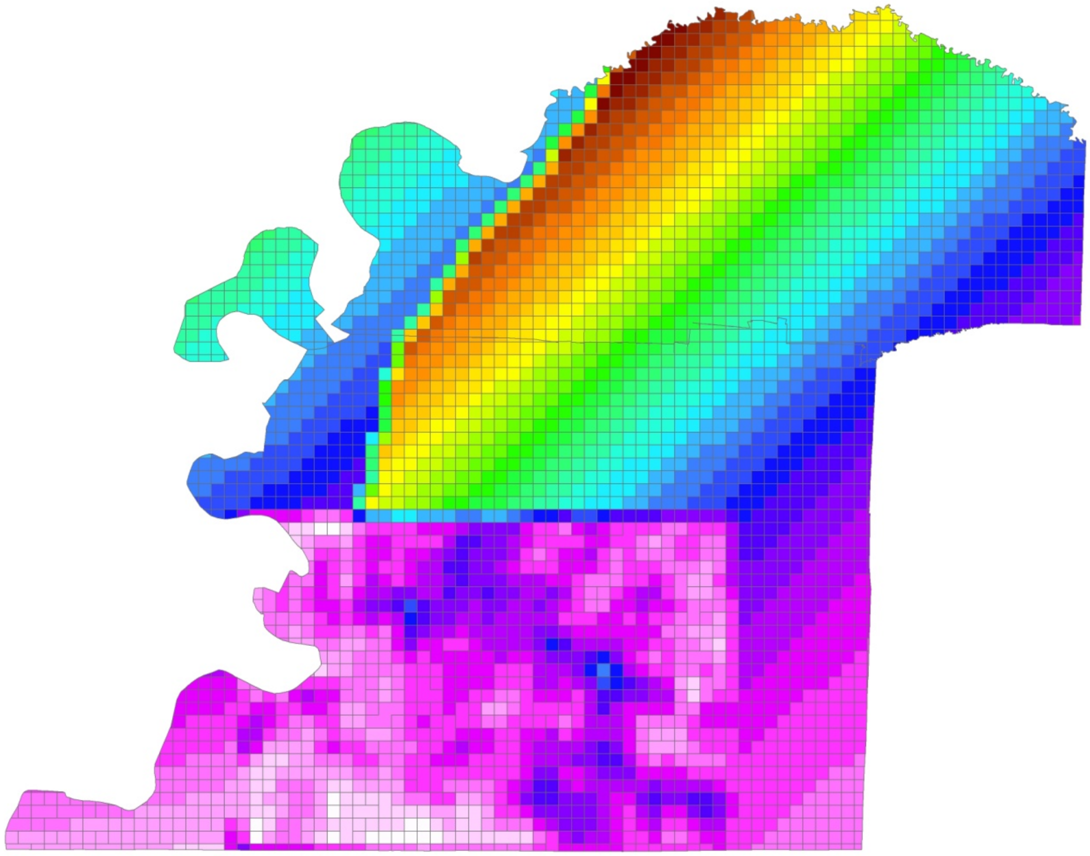

Figure C-5. 0.3 s SA, Magnitude 7.7 Range 0.450 – 1.027 g

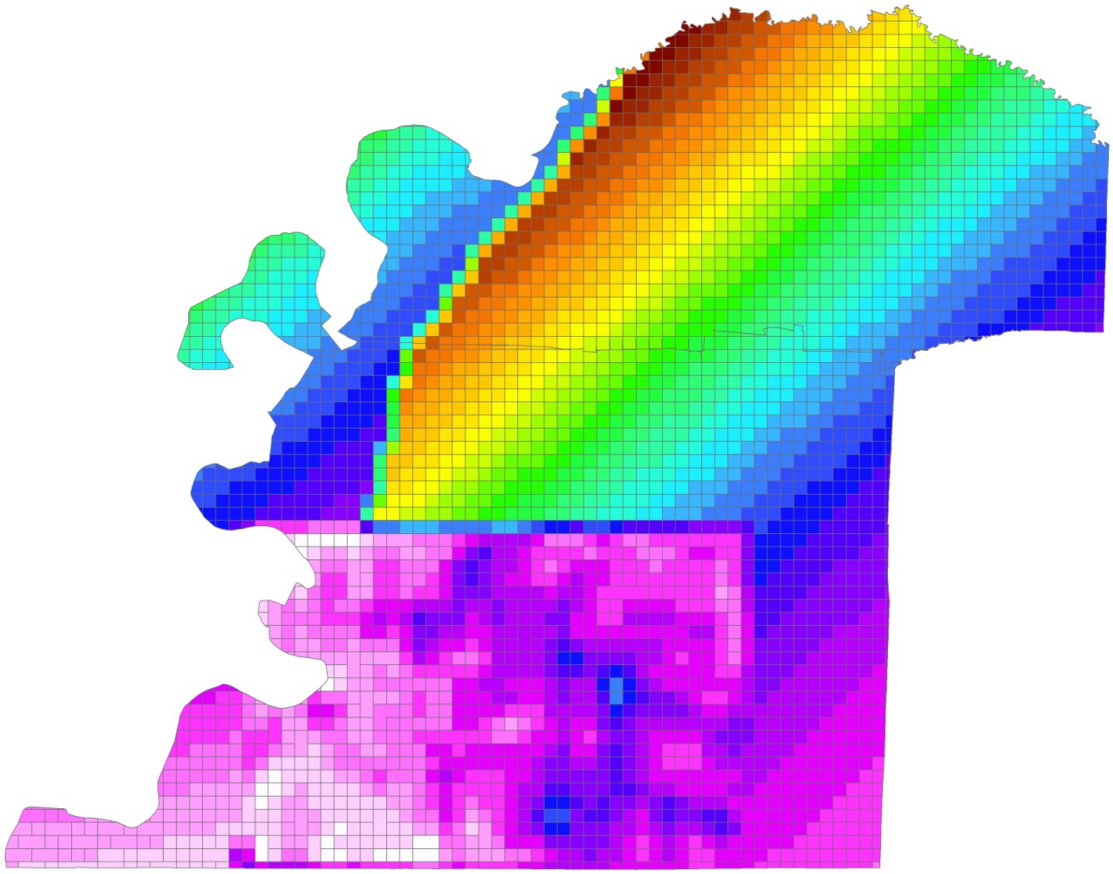

Figure C-6. 1.0 s SA, Magnitude 7.7 Range 0.410 – 0.882 g

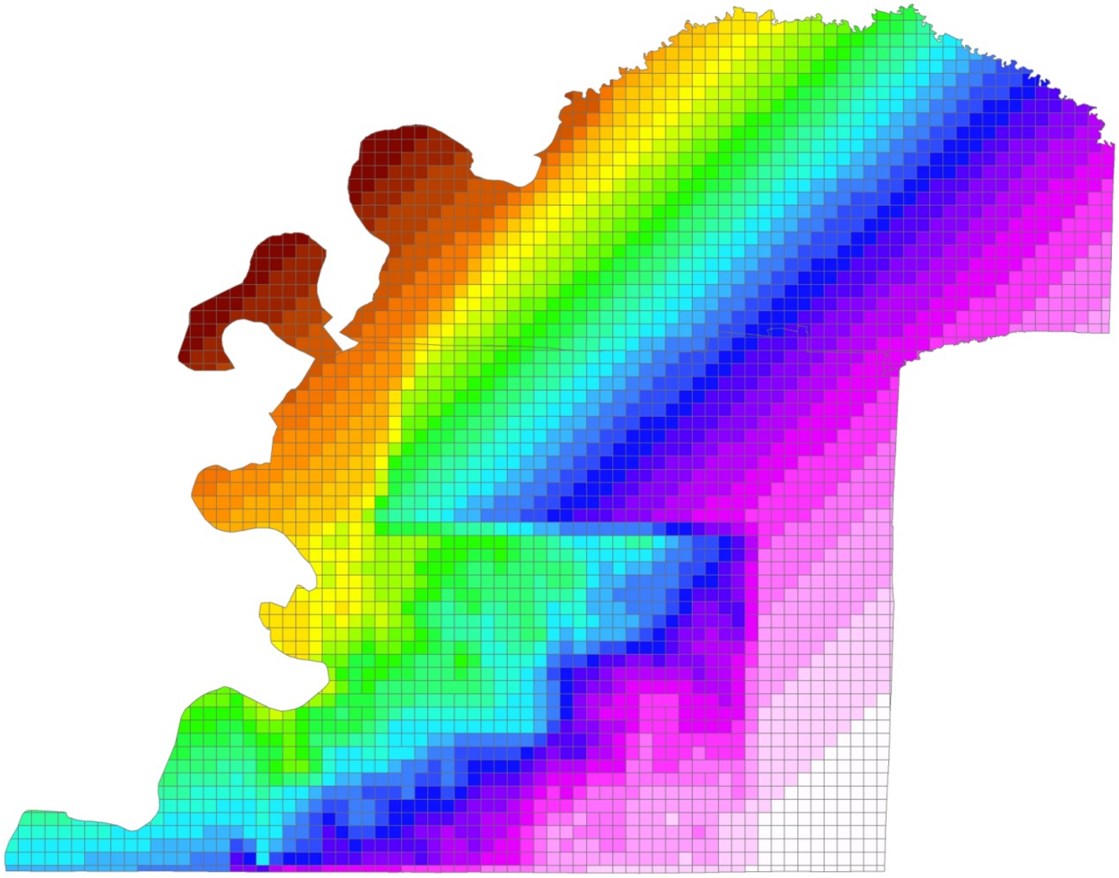

Figure C-7. PGV, Magnitude 7.7 Range 8.945– 31.782 in/sec

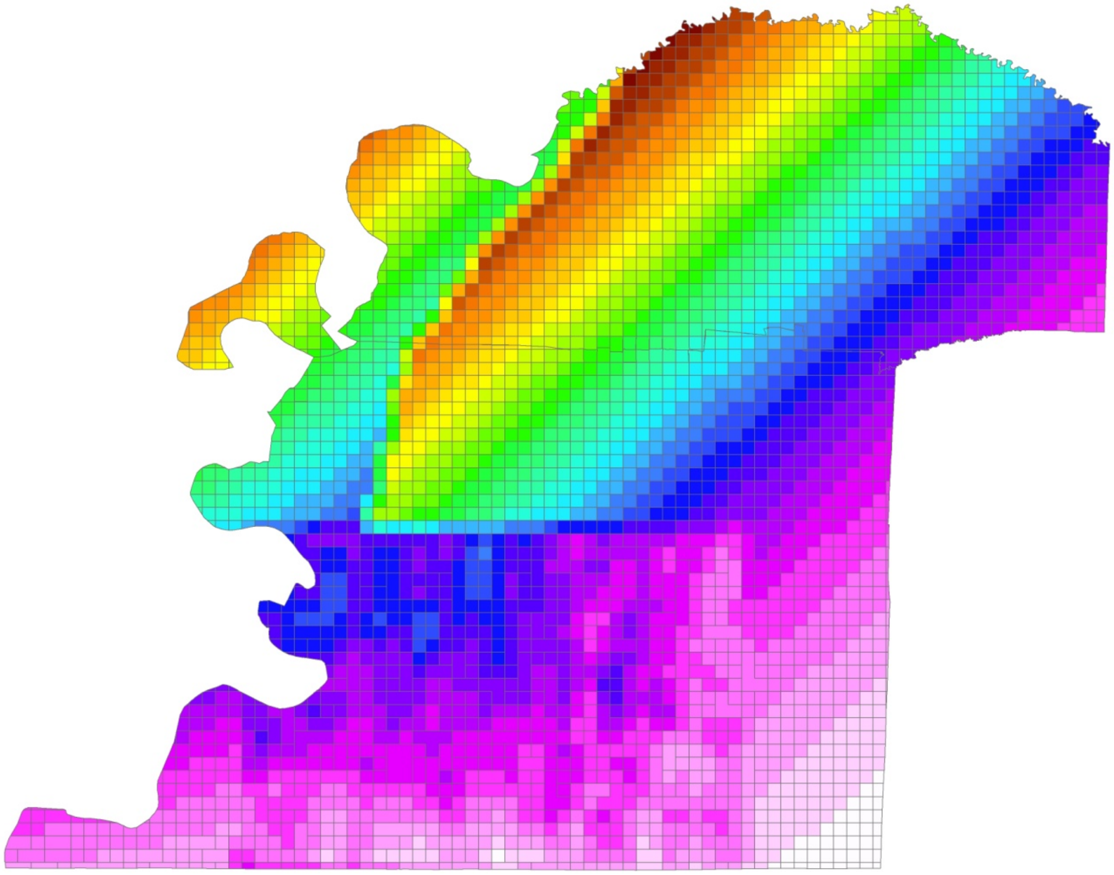

Figure C-8. PGA, Magnitude 7.7 Range 0.288 – 0.704 g

Magnitude 7.7, USGS Data

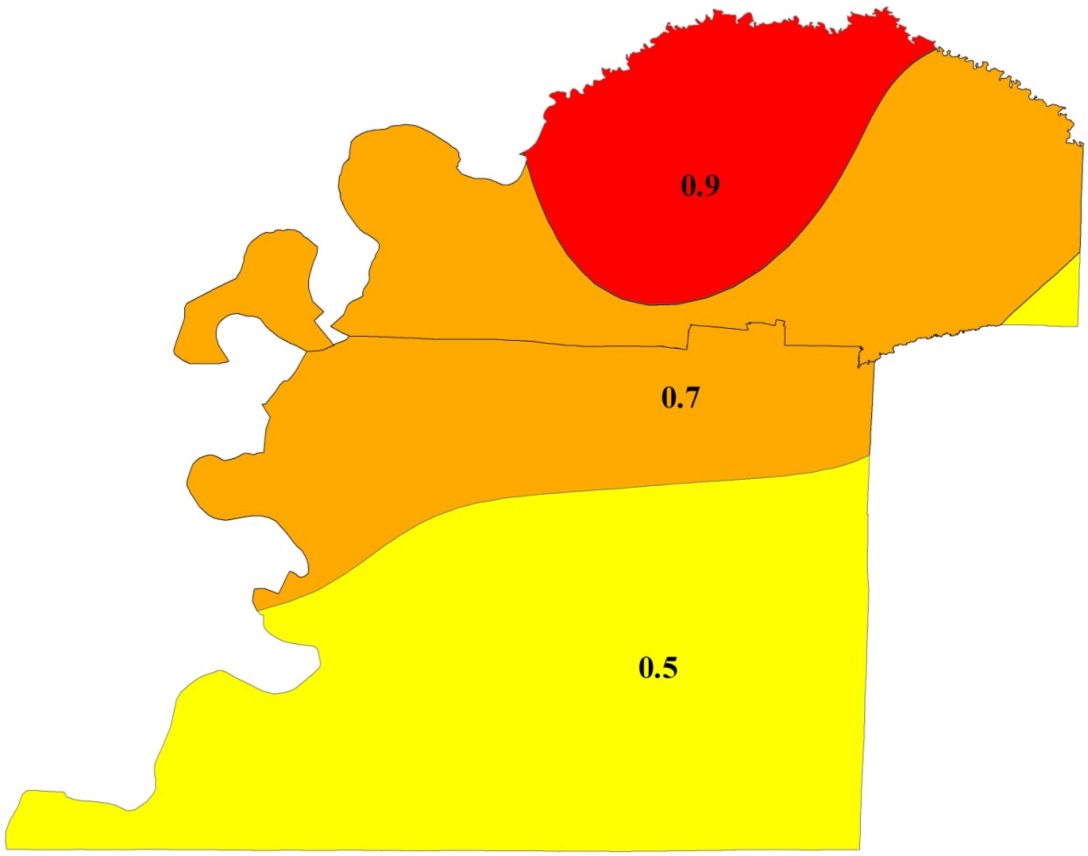

Figure C-9. 0.3 s SA, Magnitude 7.7 Range 0.5 – 0.9 g

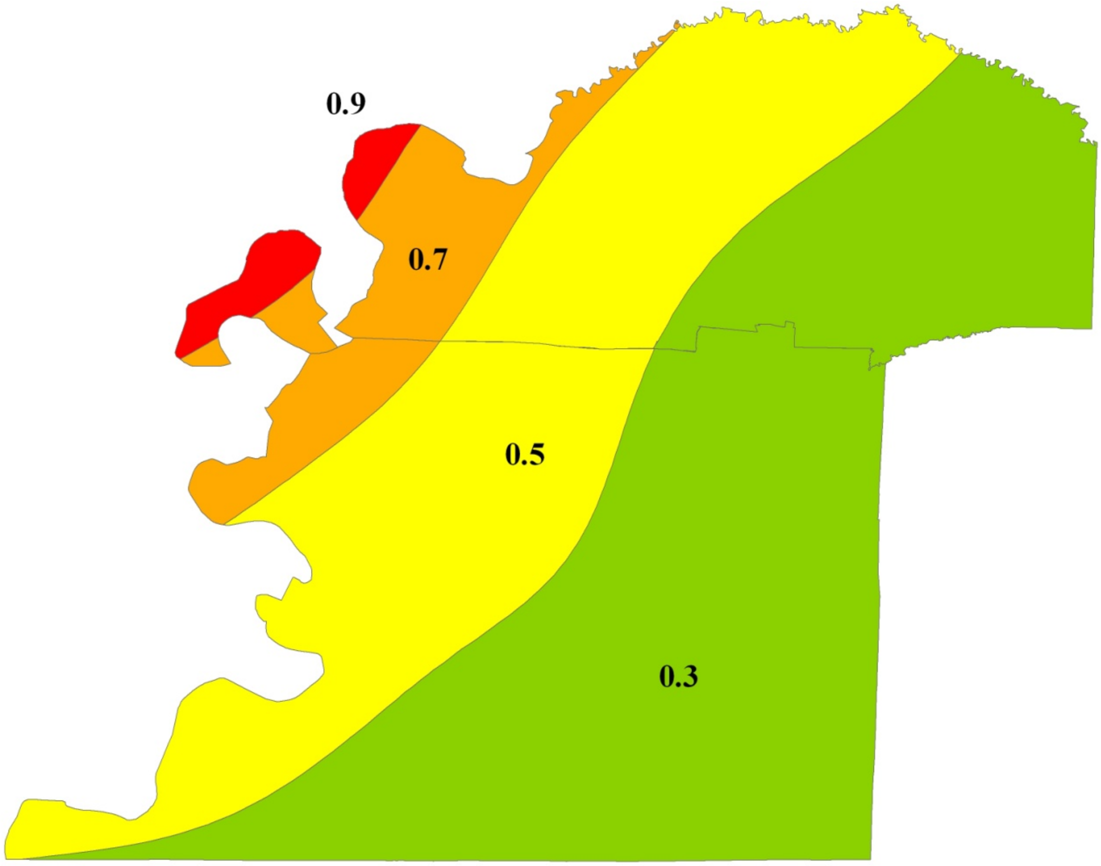

Figure C-10. 1.0 s SA, Magnitude 7.7 Range 0.3 – 0.9 g

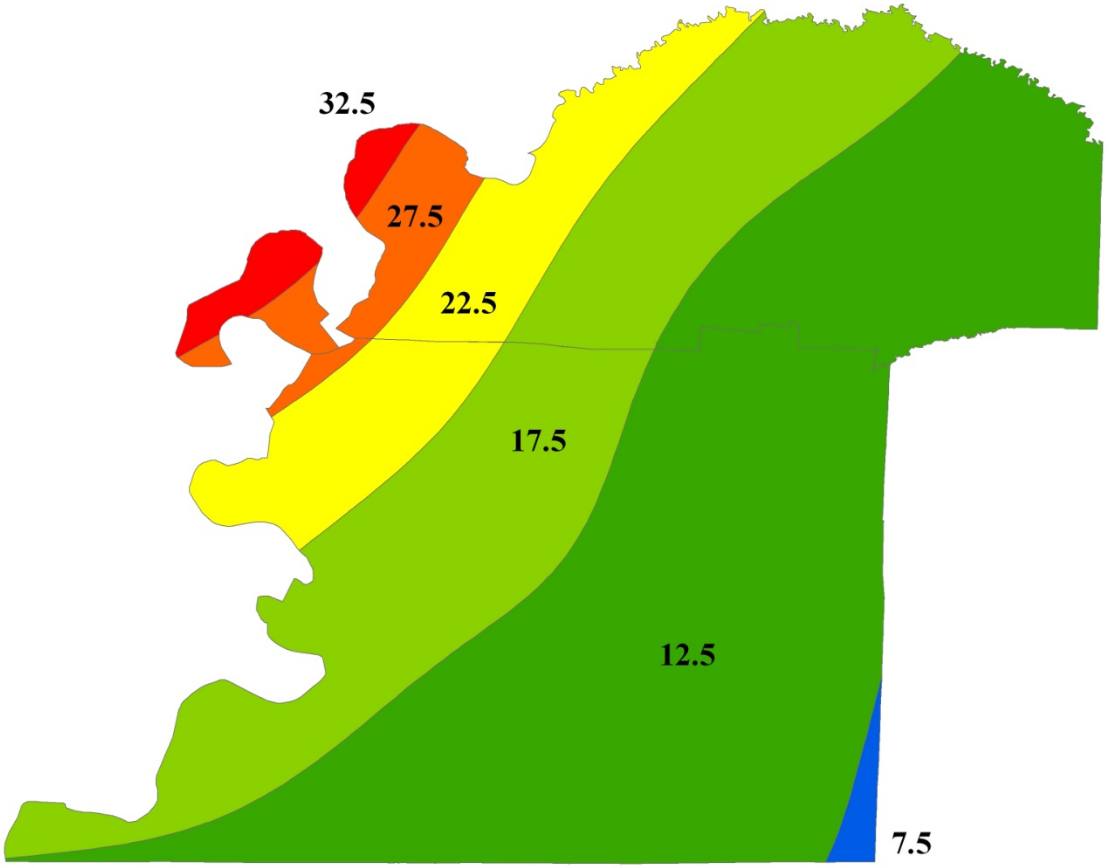

Figure C-11. PGV, Magnitude 7.7 Range 7.5 – 32.5 in/sec

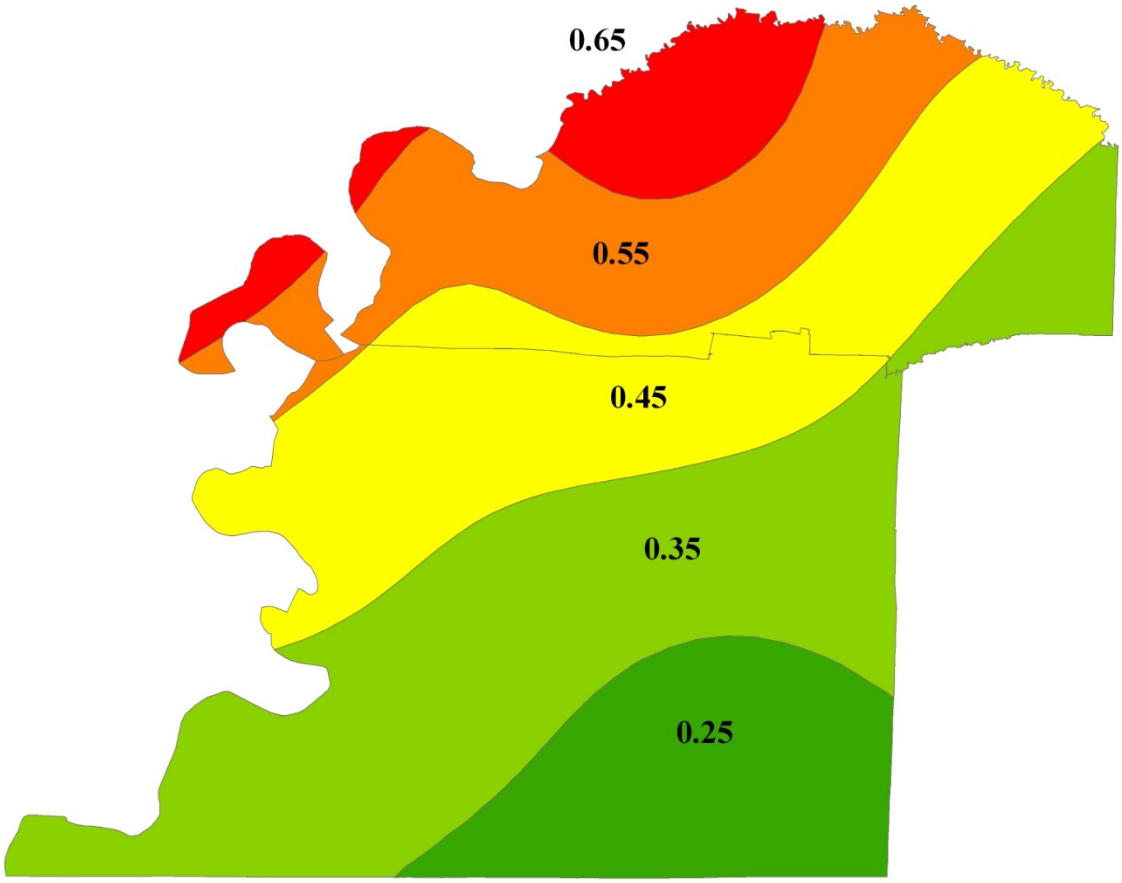

Figure C-12. PGA, Magnitude 7.7 Range 0.25 – 0.65 g

APPENDIX D: Statistical Results

Table D-1 shows buildings that have multiple structures. Table D-2 shows the different building types in the Shelby County data set while Table D-3 shows the different building types in Tipton County. Table D-4 and Table D-5 show the Shelby County and Tipton County occupancy classes, respectively. Table D-6 and Table D-7 show the Shelby County and Tipton County building construction dates, respectively. Table D-8 and Table D-9 show the Shelby County and Tipton County shape qualities, respectively. Table D-10 and Table D-11 show the Shelby County and Tipton County building heights, respectively. Table D-12 lists the structures with their corresponding building types in ascending order based upon S score. Table D-13 and Table D-14 show the Shelby County and Tipton County census tracts, respectively. Maps in this appendix show the structure distributions for the data acquired from Mize (2006), Boling (2009), as well as the additional data gathered from Shelby and Tipton Counties for this project. Figure D-1 and Figure D-2 show the Shelby County and Tipton County structure distribution, respectively, based upon data collected during this study. Figure D-3 shows the structure distribution based on data collected by Boling (2009) for Shelby County. Figure D-4 shows the structure distribution based on data collected by Mize (2006) for Shelby County; while Figure D-5 shows the up-close structure distribution based upon data collected by Mize (2006) for the University of Memphis.

Table D-1. Building Locations with Supplemental Structures

Building Location	Facility Name	Building Type	Building Location	Facility Name	Building Type
1	Structure 1	W2	33	Structure 48	W1
	Structure 2	RM1		Structure 49	S1
2	Structure 3	S1	36	Structure 52	S5
	Structure 4	UMR		Structure 53	URM
6	Structure 8	S1	46	Structure 63	S1
	Structure 9	RM1		Structure 64	S2
7	Structure 10	W2		Structure 65	C1
	Structure 11	C1	47	Structure 66	S1
8	Structure 12	S1		Structure 67	S2
	Structure 13	C3		Structure 68	C1
10	Structure 15	S1	48	Structure 69	S1
	Structure 16	RM1		Structure 70	S2
11	Structure 17	S1		Structure 71	C1
	Structure 18	C1	54	Structure 77	C3
13	Structure 20	S1		Structure 78	PC2
	Structure 21	C1	56	Structure 80	S3
15	Structure 23	S1		Structure 81	PC2
	Structure 24	C1		Structure 82	URM
17	Structure 26	S1	69	Structure 95	S1
	Structure 27	S2		Structure 96	S2
19	Structure 29	S1	70	Structure 97	S1
	Structure 30	C3		Structure 98	C3
20	Structure 31	S1	71	Structure 99	S1
	Structure 32	RM1		Structure 100	C3
25	Structure 37	C3	72	Structure 101	S1
	Structure 38	URM		Structure 102	C3
31	Structure 44	W1	73	Structure 103	S1
	Structure 45	S1		Structure 104	C3
32	Structure 46	W1	75	Structure 106	RM1
	Structure 47	S1		Structure 107	S2

Table D-1. Building Locations with Supplemental Structures (continued)

Building Location	Facility Name	Building Type	Building Location	Facility Name	Building Type
76	Structure 108	RM1	207	Structure 254	S2
	Structure 109	S2		Structure 255	C1
77	Structure 110	S5	208	Structure 256	S5
	Structure 111	S2		Structure 257	S5
80	Structure 114	RM1	210	Structure 259	W1
	Structure 115	S2		Structure 260	RM1
81	Structure 116	RM1		Structure 261	S2
	Structure 117	S2	215	Structure 266	C3
83	Structure 119	RM1		Structure 267	URM
	Structure 120	S2		Structure 268	S2
84	Structure 121	RM1		Structure 269	S2
	Structure 122	RM1	222	Structure 276	URM
85	Structure 123	RM1		Structure 277	RM1
	Structure 124	S2	228	Structure 283	C3
87	Structure 126	RM1		Structure 284	C3
	Structure 127	S2	230	Structure 286	S2
88	Structure 128	RM1		Structure 287	S5
	Structure 129	S2	231	Structure 288	C3
89	Structure 130	RM1		Structure 289	S2
	Structure 131	RM1	239	Structure 297	C3
92	Structure 134	S2		Structure 298	S3
	Structure 135	S2			
195	Structure 238	URM			
	Structure 239	RM1			
196	Structure 240	PC1			
	Structure 241	PC1			
199	Structure 244	S2			
	Structure 245	RM1			
204	Structure 250	URM			
	Structure 251	S5			

Table D-2. Shelby County Building Types

Building Type	Number of Structures in Data Set	Percent of Structures in Data Set
C1	16	6%
C2	5	2%
C3	71	26%
PC1	4	1%
PC2	2	1%
RM1	16	6%
RM2	1	0%
S1	44	16%
S2	17	6%
S3	5	2%
S4	2	1%
S5	27	10%
URM	22	8%
W1	16	6%
W2	21	8%
Total	269	100%

Table D-3. Tipton County Building Types

Building Type	Number of Structures in Data Set	Percent of Structures in Data Set
RM1	15	47%
S1	2	6%
S2	11	34%
S3	1	3%
S5	1	3%
W1	1	3%
W2	1	3%
Total	32	100%

Table D-4. Shelby County Occupancy Classes

Occupancy Class	Occupancy Class Definition	Number of Structures in Data Set	Percent of Structures in Data Set
COM4	Professionals and Technical Services	2	1%
COM7	Medical Office and Clinic	1	0%
COM8	Entertainment and Recreation	46	17%
COM9	Theatres	2	1%
COM10	Parking Garages	2	1%
EDU1	Grade Schools and Admin. Offices	7	3%
EDU2	Colleges and Universities	100	37%
GOV1	Government-General Services	1	0%
REL1	Churches and Non-Profit Organizations	77	29%
RES1	Single Family Dwellings	1	0%
RES3A	Duplex	1	0%
RES3C	5 to 9 Units	5	2%
RES3D	10 to 19 Units	7	3%
RES4	Temporary Lodging	1	0%
RES5	Institutional Dormitories	16	6%
Total		269	100%

Table D-5. Tipton County Occupancy Classes

Occupancy Class	Occupancy Class Definition	Number of Structures in Data Set	Percent of Structures in Data Set
COM6	Hospitals	1	3%
COM7	Medical Office and Clinic	1	3%
EDU1	Grade Schools and Admin. Offices	26	81%
RES6	Nursing Homes	4	13%
Total		32	100%

Table D-6. Shelby County Building Construction Dates

Decade	Number of Structures in Data Set	Percent of Structures in Data Set
1850-1859	2	1%
1860-1869	0	0%
1870-1879	0	0%
1880-1889	0	0%
1890-1899	0	0%
1900-1909	0	0%
1910-1919	4	1%
1920-1929	4	1%
1930-1939	5	2%
1940-1949	6	2%
1950-1959	27	10%
1960-1969	51	19%
1970-1979	50	19%
1980-1989	43	16%
1990-1999	47	17%
2000-2009	21	8%
2010-2019	9	3%
Total	269	100%

Table D-7. Tipton County Building Construction Dates

Decade	Number of Structures in Data Set	Percent of Structures in Data Set
1950-1959	1	3%
1960-1969	3	9%
1970-1979	7	22%
1980-1989	8	25%
1990-1999	12	38%
2000-2009	1	3%
Total	32	100%

Table D-8. Shelby County Shape Qualities

Irregularity	Number of Structures in Data Set	Percent of Structures in Data Set
Plan	43	16%
Vertical	29	11%
No Irregularity	47	17%
Both Irregularities	150	56%
Total	269	100%

Table D-9. Tipton County Shape Qualities

Irregularity	Number of Structures in Data Set	Percent of Structures in Data Set
Plan	0	0%
Vertical	0	0%
No Irregularity	0	0%
Both Irregularities	32	100%
Total	32	100%

Table D-10. Shelby County Building Heights

Height	Number of Structures in Data Set	Percent of Structures in Data Set
Low Rise	226	75%
Mid Rise	39	13%
High Rise	4	1%
Total	269	89%

Table D-11. Tipton County Building Heights

Height	Number of Structures in Data Set	Percent of Structures in Data Set
Low Rise	32	100%
Mid Rise	0	0%
High Rise	0	0%
Total	32	100%

Table D-12. Structure Order by S Score

Structure	Building Type	S-Score	Structure	Building Type	S-Score
Structure 5	C1	-1.3	Structure 168	C3	-0.5
Structure 11	C1	-1.3	Structure 171	C3	-0.5
Structure 18	C1	-1.3	Structure 204	URM	-0.5
Structure 21	C1	-1.3	Structure 215	C3	-0.5
Structure 24	C1	-0.9	Structure 220	URM	-0.5
Structure 190	C1	-0.9	Structure 221	URM	-0.5
Structure 4	URM	-0.7	Structure 264	W2	-0.5
Structure 255	C1	-0.7	Structure 267	URM	-0.5
Structure 1	W2	-0.5	Structure 270	URM	-0.5
Structure 10	W2	-0.5	Structure 271	C3	-0.5
Structure 13	C3	-0.5	Structure 276	URM	-0.5
Structure 36	C3	-0.5	Structure 282	URM	-0.5
Structure 37	C3	-0.5	Structure 283	C3	-0.5
Structure 38	URM	-0.5	Structure 285	C3	-0.5
Structure 53	URM	-0.5	Structure 291	C3	-0.5
Structure 54	C3	-0.5	Structure 292	C3	-0.5
Structure 57	C3	-0.5	Structure 295	URM	-0.5
Structure 60	C3	-0.5	Structure 297	C3	-0.5
Structure 61	C3	-0.5	Structure 107	S2	-0.4
Structure 62	C3	-0.5	Structure 115	S2	-0.4
Structure 77	C3	-0.5	Structure 117	S2	-0.4
Structure 78	PC2	-0.5	Structure 120	S2	-0.4
Structure 81	PC2	-0.5	Structure 124	S2	-0.4
Structure 82	URM	-0.5	Structure 127	S2	-0.4
Structure 83	C3	-0.5	Structure 129	S2	-0.4
Structure 84	C3	-0.5	Structure 278	S2	-0.4
Structure 86	C3	-0.5	Structure 2	RM1	-0.3
Structure 100	C3	-0.5	Structure 6	S1	-0.3
Structure 102	C3	-0.5	Structure 7	S1	-0.3
Structure 104	C3	-0.5	Structure 12	S1	-0.3
Structure 150	URM	-0.5	Structure 15	S1	-0.3
Structure 155	URM	-0.5	Structure 16	RM1	-0.3
Structure 164	W2	-0.5	Structure 17	S1	-0.3
Structure 166	C3	-0.5	Structure 20	S1	-0.3

Table D-12. Structure Order by S Score (continued)

Structure	Building Type	S Score	Structure	Building Type	S Score
Structure 22	S1	-0.3	Structure 152	S1	-0.3
Structure 23	S1	-0.3	Structure 158	C3	-0.3
Structure 29	S1	-0.3	Structure 178	C3	-0.3
Structure 30	C3	-0.3	Structure 241	PC1	-0.3
Structure 31	S1	-0.3	Structure 242	URM	-0.3
Structure 32	RM1	-0.3	Structure 279	C3	-0.3
Structure 33	S1	-0.3	Structure 296	RM1	-0.3
Structure 34	S1	-0.3	Structure 3	S1	-0.1
Structure 35	S1	-0.3	Structure 52	S5	-0.1
Structure 50	S1	-0.3	Structure 97	S1	-0.1
Structure 55	C3	-0.3	Structure 151	S5	-0.1
Structure 76	C2	-0.3	Structure 154	S5	-0.1
Structure 87	C2	-0.3	Structure 183	S5	-0.1
Structure 92	S1	-0.3	Structure 192	S5	-0.1
Structure 98	C3	-0.3	Structure 200	S5	-0.1
Structure 99	S1	-0.3	Structure 243	S5	-0.1
Structure 101	S1	-0.3	Structure 251	S5	-0.1
Structure 103	S1	-0.3	Structure 256	S5	-0.1
Structure 105	S1	-0.3	Structure 258	S5	-0.1
Structure 106	RM1	-0.3	Structure 262	C3	-0.1
Structure 113	S1	-0.3	Structure 263	S5	-0.1
Structure 114	RM1	-0.3	Structure 266	C3	-0.1
Structure 116	RM1	-0.3	Structure 280	S5	-0.1
Structure 118	RM1	-0.3	Structure 281	C3	-0.1
Structure 119	RM1	-0.3	Structure 287	S5	-0.1
Structure 121	RM1	-0.3	Structure 294	S5	-0.1
Structure 122	RM1	-0.3	Structure 39	URM	0
Structure 123	RM1	-0.3	Structure 157	C3	0.0
Structure 126	RM1	-0.3	Structure 172	C3	0.0
Structure 128	RM1	-0.3	Structure 205	C3	0.0
Structure 130	RM1	-0.3	Structure 223	C3	0.0
Structure 131	RM1	-0.3	Structure 238	URM	0
Structure 133	RM1	-0.3	Structure 284	C3	0
Structure 149	C3	-0.3	Structure 110	S5	0.1

Table D-12. Structure Order by S Score (continued)

Structure	Building Type	S Score	Structure	Building Type	S Score
Structure 257	S5	0.1	Structure 217	C3	0.8
Structure 274	S5	0.1	Structure 299	W2	0.8
Structure 301	S5	0.1	Structure 56	S5	0.9
Structure 25	S1	0.2	Structure 248	S5	0.9
Structure 28	RM1	0.2	Structure 293	S2	0.9
Structure 213	C3	0.2	Structure 79	URM	1.0
Structure 239	RM1	0.2	Structure 156	URM	1.0
Structure 260	RM1	0.2	Structure 169	C3	1.0
Structure 14	S5	0.3	Structure 175	C3	1.0
Structure 153	S5	0.4	Structure 181	C3	1.0
Structure 173	S5	0.4	Structure 196	C3	1.0
Structure 231	S5	0.4	Structure 199	C3	1.0
Structure 75	C3	0.5	Structure 212	C3	1.0
Structure 174	C3	0.5	Structure 219	C3	1.0
Structure 176	C3	0.5	Structure 230	C3	1.0
Structure 201	URM	0.5	Structure 232	URM	1.0
Structure 250	URM	0.5	Structure 227	C1	1.1
Structure 300	C3	0.5	Structure 42	S1	1.2
Structure 41	RM1	0.7	Structure 167	C3	1.2
Structure 43	RM1	0.7	Structure 170	C3	1.2
Structure 58	C3	0.7	Structure 184	C3	1.2
Structure 59	C3	0.7	Structure 187	C1	1.2
Structure 85	PC1	0.7	Structure 188	C1	1.2
Structure 179	C3	0.7	Structure 189	C3	1.2
Structure 191	C3	0.7	Structure 194	C3	1.2
Structure 195	C3	0.7	Structure 198	C3	1.2
Structure 203	C3	0.7	Structure 208	C3	1.2
Structure 214	C3	0.7	Structure 218	C3	1.2
Structure 226	C1	0.7	Structure 240	PC1	1.2
Structure 233	RM1	0.7	Structure 259	W1	1.2
Structure 288	C3	0.7	Structure 265	RM1	1.2
Structure 290	PC1	0.7	Structure 65	C1	1.3
Structure 180	S5	0.8	Structure 68	C1	1.3
Structure 216	C3	0.8	Structure 71	C1	1.3

Table D-12. Structure Order by S Score (continued)

Structure	Building Type	S Score	Structure	Building Type	S Score
Structure 74	W1	1.4	Structure 91	W1	1.9
Structure 125	W1	1.4	Structure 185	W1	1.9
Structure 182	S5	1.4	Structure 225	W1	1.9
Structure 211	RM2	1.4	Structure 73	S3	2.0
Structure 222	S5	1.4	Structure 137	W2	2.0
Structure 80	S3	1.5	Structure 141	W2	2.0
Structure 138	W2	1.5	Structure 143	W2	2.0
Structure 139	W2	1.5	Structure 145	W2	2.0
Structure 140	W2	1.5	Structure 148	W2	2.0
Structure 142	W2	1.5	Structure 160	W2	2.0
Structure 144	W2	1.5	Structure 186	C2	2.0
Structure 146	W2	1.5	Structure 193	S5	2.0
Structure 147	W2	1.5	Structure 298	S3	2
Structure 224	W2	1.5	Structure 26	S1	2.1
Structure 246	W2	1.5	Structure 40	S1	2.1
Structure 247	S3	1.5	Structure 45	S1	2.1
Structure 206	C2	1.6	Structure 47	S1	2.1
Structure 27	S2	1.8	Structure 49	S1	2.1
Structure 64	S2	1.8	Structure 51	S1	2.1
Structure 67	S2	1.8	Structure 63	S1	2.1
Structure 70	S2	1.8	Structure 66	S1	2.1
Structure 96	S2	1.8	Structure 69	S1	2.1
Structure 109	S2	1.8	Structure 72	S1	2.1
Structure 111	S2	1.8	Structure 93	S1	2.1
Structure 134	S2	1.8	Structure 94	S1	2.1
Structure 135	S2	1.8	Structure 95	S1	2.1
Structure 229	C1	1.8	Structure 112	S3	2.1
Structure 237	S2	1.8	Structure 197	S1	2.1
Structure 244	S2	1.8	Structure 252	S1	2.1
Structure 254	S2	1.8	Structure 253	S1	2.1
Structure 268	S2	1.8	Structure 8	S1	2.3
Structure 269	S2	1.8	Structure 19	S1	2.3
Structure 272	S2	1.8	Structure 177	S1	2.3
Structure 286	S2	1.8	Structure 234	S4	2.3

Table D-12. Structure Order by S Score (continued)

Structure	Building Type	S Score
Structure 261	S2	2.3
Structure 163	S3	2.6
Structure 202	S1	2.8
Structure 209	C1	2.8
Structure 132	W2	2.9
Structure 228	S1	3.2
Structure 236	S4	3.3
Structure 289	S2	3.3
Structure 9	RM1	3.5
Structure 108	RM1	3.5
Structure 136	RM1	3.5
Structure 44	W1	3.8
Structure 46	W1	3.8
Structure 48	W1	3.8
Structure 88	W1	3.8
Structure 273	S2	3.8
Structure 162	W1	3.9
Structure 249	RM1	4
Structure 89	W1	4.3
Structure 90	W1	4.3
Structure 159	W1	4.4
Structure 161	W1	4.4
Structure 165	W1	4.4
Structure 210	W1	4.4
Structure 235	RM1	4.5
Structure 277	RM1	4.5
Structure 207	C2	5.0
Structure 245	RM1	5
Structure 275	W2	5.4

Table D-13. Shelby County Census Tracts

Count	Shelby County Census Tracts	Count	Shelby County Census Tracts
1	47157000200	38	47157020300
2	47157000500	39	47157020400
3	47157000800	40	47157020522
4	47157001200	41	47157020530
5	47157001900	42	47157020541
6	47157002100	43	47157020610
7	47157002800	44	47157020621
8	47157003100	45	47157020622
9	47157003200	46	47157020631
10	47157003300	47	47157020632
11	47157003600	48	47157020651
12	47157004200	49	47157020830
13	47157004600	50	47157021010
14	47157005000	51	47157021121
15	47157005300	52	47157021137
16	47157006400	53	47157021200
17	47157006500	54	47157021310
18	47157006700	55	47157021341
19	47157006900	56	47157021430
20	47157007000	57	47157021510
21	47157007100	58	47157021520
22	47157007300	59	47157021611
23	47157007400	60	47157021620
24	47157007500	61	47157021721
25	47157007810	62	47157021723
26	47157008600	63	47157021732
27	47157008700	64	47157021741
28	47157009000	65	47157021752
29	47157009200	66	47157021900
30	47157009400	67	47157022010
31	47157009500	68	47157022111
32	47157009700	69	47157022112
33	47157009900	70	47157022120
34	47157010120	71	47157022220
35	47157010210	72	47157022321
36	47157010710	73	47157022330
37	47157010900		

Table D-14. Tipton County Census Tracts

Count	Tipton County Census Tracts
1	47167040100
2	47167040301
3	47167040500
4	47167040601
5	47167040602
6	47167040700
7	47167040800

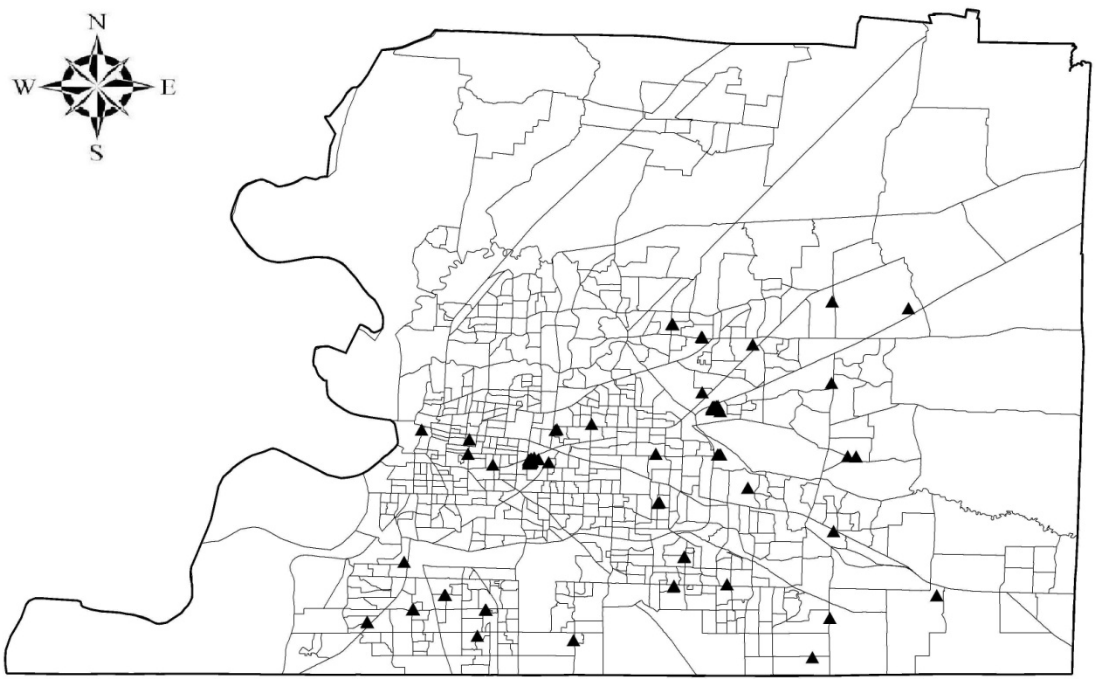

Figure D-1. Shelby County Structure Distribution for This Study

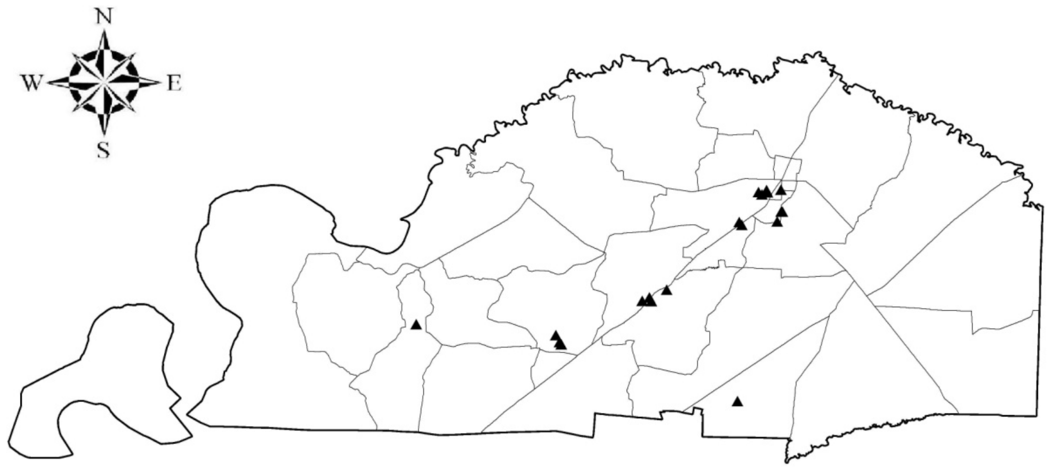

Figure D-2. Tipton County Structure Distribution for This Study

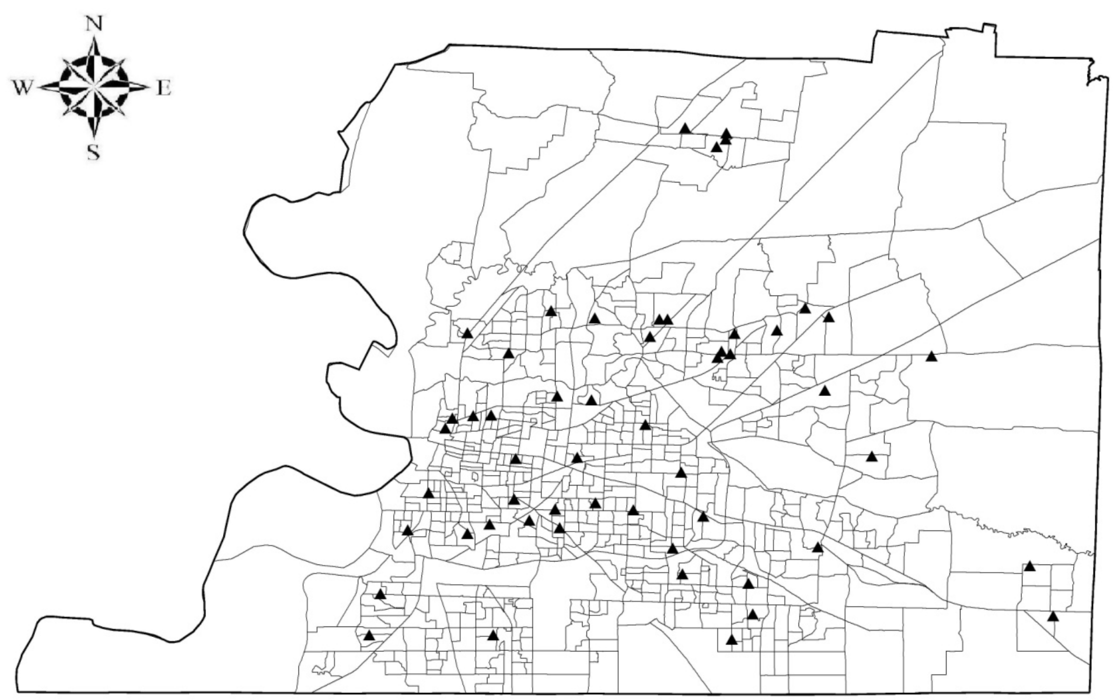

Figure D-3. Boling (2009) Shelby County Structure Distribution

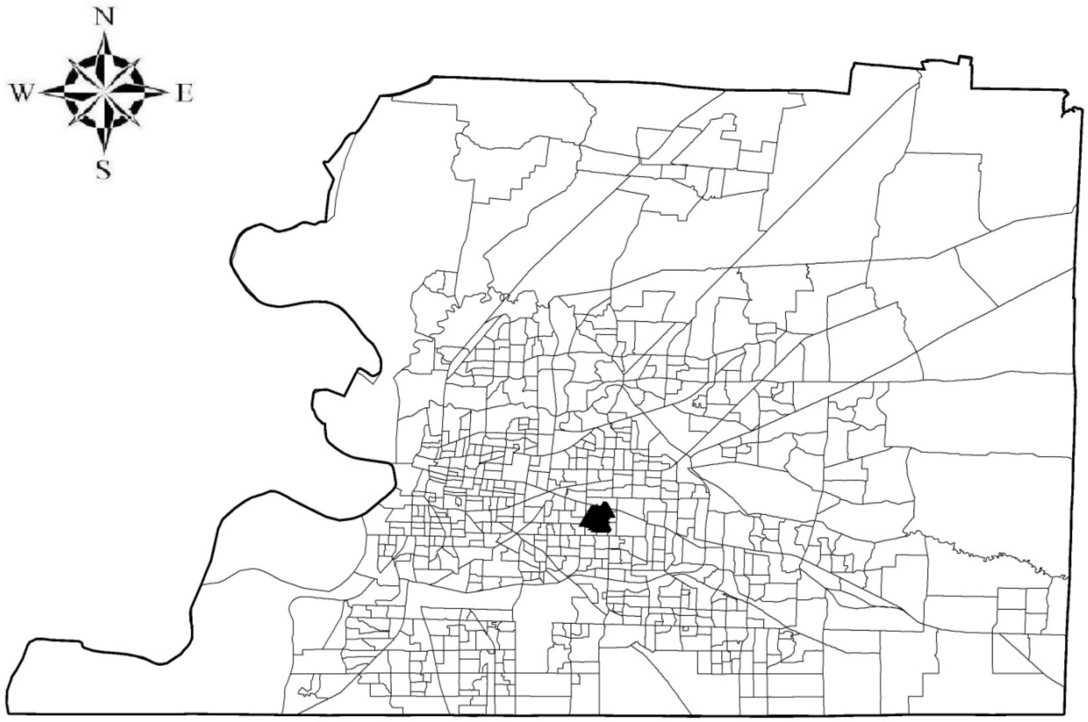

Figure D-4. Mize (2006) Shelby County Structure Distribution

Figure D-5. Mize (2006) University of Memphis Distribution

APPENDIX E: Damage State Definitions by Building Type

Descriptions of the damage states, structural and non-structural, for each of the 15 building types are listed below (HAZUS-MH MR3 Technical Manual, Section 5.3.1 2006a).

Structural Damage

Wood, Light Frame (W1):

Slight Structural Damage: Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.

Moderate Structural Damage: Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.

Extensive Structural Damage: Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-story” configurations; small foundations cracks.

Complete Structural Damage: Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with complete damage is expected to be collapsed.

Wood, Commercial and Industrial (W2):

Slight Structural Damage: Small cracks at corners of door and window openings and wall-ceiling intersections; small cracks on stucco and plaster walls. Some slippage may be observed at bolted connections.

Moderate Structural Damage: Larger cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by cracks in stucco and gypsum wall panels; minor slack (less than 1/8” extension) in diagonal rod bracing requiring re-tightening; minor lateral set at store fronts and other large openings; small cracks or wood splitting may be observed at bolted connections.

Extensive Structural Damage: Large diagonal cracks across shear wall panels; large slack in diagonal rod braces and/or broken braces; permanent lateral movement of floors and roof; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “soft-story” configurations; bolt slippage and wood splitting at bolted connections.

Complete Structural Damage: Structure may have large permanent lateral displacement, may collapse or be in imminent danger of collapse due to failed shear walls, broken brace rods or failed framing connections; it may fall its foundations; large cracks in the foundations. Approximately 3% of the total area of W2 buildings with complete damage is expected to be collapsed.

<u>Steel Moment Frame (S1):</u>

Slight Structural Damage: Minor deformations in connections or hairline cracks in few welds.

Moderate Structural Damage: Some steel members have yielded exhibiting observable permanent rotations at connections; few welded connections may exhibit major cracks through welds or few bolted connections may exhibit broken bolts or enlarged bolt holes.

Extensive Structural Damage: Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.

Complete Structural Damage: Significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building. Approximately 8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S1 buildings with Complete damage is expected to be collapsed.

<u>Steel Braced Frame (S2):</u>

Slight Structural Damage: Few steel braces have yielded which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.

Moderate Structural Damage: Some steel braces have yielded exhibiting observable stretching and/or buckling of braces; few braces, other members or connections have indications of reaching their ultimate capacity exhibited by buckled braces, cracked welds, or failed bolted connections.

Extensive Structural Damage: Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of structure is possible due to failure of critical elements or connections.

Complete Structural Damage: Most the structural elements have reached their ultimate capacities or some critical members or connections have failed resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building. Approximately 8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S2 buildings with Complete damage is expected to be collapsed.

Steel Light Frame (S3):

These structures are mostly single story structures combining rod-braced frames in one direction and moment frames in the other. Due to repetitive nature of the structural systems, the type of damage to structural members is expected to be rather uniform throughout the structure.

Slight Structural Damage: Few steel rod braces have yielded which may be indicated by minor sagging of rod braces. Minor cracking at welded connections or minor deformations at bolted connections of moment frames may be observed.

Moderate Structural Damage: Most steel braces have yielded exhibiting observable significantly sagging rod braces; few brace connections may be broken. Some weld cracking may be observed in the moment frame connections.

Extensive Structural Damage: Significant permanent lateral deformation of the structure due to broken brace rods, stretched anchor bolts and permanent deformations at moment frame members. Some screw or welded attachments of roof and wall siding to steel framing may be broken. Some purlin and girt connections may be broken.

Complete Structural Damage: Structure is collapsed or in imminent danger of collapse due to broken rod bracing, failed anchor bolts or failed structural members or connections. Approximately 3% of the total area of S3 buildings with complete damage is expected to be collapsed.

Steel Frame with Cast-In-Place Concrete Shear Walls (S4):

This is a "composite" structural system where primary lateral-force-resisting system is the concrete shear walls. Hence, slight, Moderate and Extensive damage states are likely to be determined by the shear walls while the collapse damage state would be determined by the failure of the structural frame.

Slight Structural Damage: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities exhibited by larger diagonal cracks and concrete spalling at wall ends.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; few walls have reached or exceeded their ultimate capacity exhibited by large through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. Partial collapse may occur due to failed connections of steel framing to concrete walls. Some damage may be observed in steel frame connections.

Complete Structural Damage: Structure may be in danger of collapse or collapse due to total failure of shear walls and loss of stability of the steel frames. Approximately 8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S4 buildings with Complete damage is expected to be collapsed.

Steel Frame with Unreinforced Masonry Infill Walls (S5):

This is a "composite" structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the steel frames "braced" by the infill walls acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry "struts") and the steel frame loses its stability.

Slight Structural Damage: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.

Moderate Structural Damage: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections.

Extensive Structural Damage: Most infill walls exhibit large cracks; some bricks may be dislodged and fall; some infill walls may bulge out-of-plane; few walls may fall off partially or fully; some steel frame connections may have failed. Structure may exhibit permanent lateral deformation or partial collapse due to failure of some critical members.

Complete Structural Damage: Structure is collapsed or in danger of imminent collapse due to total failure of many infill walls and loss of stability of the steel frames. Approximately 8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S5 buildings with complete damage is expected to be collapsed.

Reinforced Concrete Moment Resisting Frames (C1):

Slight Structural Damage: Flexural or shear type hairline cracks in some beams and columns near joints or within joints.

Moderate Structural Damage: Most beams and columns exhibit hairline cracks. In ductile frames some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.

Extensive Structural Damage: Some of the frame elements have reached their ultimate capacity indicated in ductile frames by large flexural cracks, spalled concrete and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, or broken ties or buckled main reinforcement in columns which may result in partial collapse.

Complete Structural Damage: Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of C1 buildings with complete damage is expected to be collapsed.

Concrete Shear Walls (C2):

Slight Structural Damage: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity indicated by larger diagonal cracks and concrete spalling at wall ends.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement or rotation of narrow walls with inadequate foundations. Partial collapse may occur due to failure of nonductile columns not designed to resist lateral loads.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of C2 buildings with complete damage is expected to be collapsed.

Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3):

This is a “composite” structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the concrete frame “braced” by the infill acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry “struts”) and the frame loses stability, or when the concrete columns suffer shear failures due to reduced effective height and the high shear forces imposed on them by the masonry compression struts.

Slight Structural Damage: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.

Moderate Structural Damage: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns.

Extensive Structural Damage: Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and nonductile failure of the concrete beams and columns. Approximately 15% (low-rise), 13% (mid-rise) or 5% (high-rise) of the total area of C3 buildings with complete damage is expected to be collapsed.

Precast Concrete Tilt-Up Walls (PC1):

Slight Structural Damage: Diagonal hairline cracks on concrete shear wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor concrete spalling at few locations; minor separation of walls from the floor and roof diaphragms; hairline cracks around metal connectors between wall panels and at connections of beams to walls.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; larger cracks in walls with door or window openings; few shear walls have exceeded their yield capacities indicated by larger diagonal cracks and concrete spalling. Cracks may appear at top of walls near panel intersections indicating "chord" yielding. Some walls may have visibly pulled away from the roof. Some welded panel connections may have been broken, indicated by spalled concrete around connections. Some spalling may be observed at the connections of beams to walls.

Extensive Structural Damage: In buildings with relatively large area of wall openings most concrete shear walls have exceeded their yield capacities and some have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from the failure of the wall-to-diaphragm anchorages sometimes with falling of wall panels.

Complete Structural Damage: Structure is collapsed or is in imminent danger of collapse due to failure of the wall-to-roof anchorages, splitting of ledgers, or failure of plywood-to-ledger nailing; failure of beams connections at walls; failure of roof or floor diaphragms; or, failure of the wall panels. Approximately 15% of the total area of PC1 buildings with complete damage is expected to be collapsed.

<u>Precast Concrete Frames with Concrete Shear Walls (PC2):</u>

Slight Structural Damage: Diagonal hairline cracks on most shear wall surfaces; minor concrete spalling at few connections of precast members.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded their yield capacities indicated by larger cracks and concrete spalling at wall ends; observable distress or movement at connections of precast frame connections, some failures at metal inserts and welded connections.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; some walls may have reached their ultimate capacities indicated by large, through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. Some critical precast frame connections may have failed resulting partial collapse.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of the shear walls and/or failures at precast frame connections. Approximately 15% (low-rise), 13% (mid-rise) or 10% (high-rise) of the total area of PC2 buildings with complete damage is expected to be collapsed.

<u>Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1):</u>

Slight Structural Damage: Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor separation of walls from the floor and roof diaphragms.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger diagonal cracks. Some walls may have visibly pulled away from the roof.

Extensive Structural Damage: In buildings with relatively large area of wall openings most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from failure of the wall-to-diaphragm anchorages or the connections of beams to walls.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of the wall anchorages or due to failure of the wall panels. Approximately 13% (low-rise) or 10% (mid-rise) of the total area of RM1 buildings with complete damage is expected to be collapsed.

Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2):

Slight Structural Damage: Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger cracks.

Extensive Structural Damage: In buildings with relatively large area of wall openings most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities exhibited by large, through-the wall diagonal cracks and visibly buckled wall reinforcement. The diaphragms may also exhibit cracking

Complete Structural Damage: Structure is collapsed or is in imminent danger of collapse due to failure of the walls. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of RM2 buildings with Complete damage is expected to be collapsed.

Unreinforced Masonry Bearing Walls (URM):

Slight Structural Damage: Diagonal, stair-step hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; movements of lintels; cracks at the base of parapets.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; some masonry may fall from walls or parapets.

Extensive Structural Damage: In buildings with relatively large area of wall openings most walls have suffered extensive cracking. Some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their supports.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of the walls. Approximately 15% of the total area of URM buildings with complete damage is expected to be collapsed.

Nonstructural Damage

Four damage states are used to describe nonstructural damage: Slight, Moderate, Extensive and Complete nonstructural damage. Nonstructural damage is considered to be independent of the structural model building type (i.e. partitions, ceilings, cladding, etc. are assumed to incur the same damage when subjected to the same interstory drift or floor acceleration whether they are in a steel frame building or in a concrete shear wall building), consequently, building-specific damage state descriptions are not meaningful. Instead, general descriptions of nonstructural damage states are provided for common nonstructural systems.

Damage to drift-sensitive nonstructural components is primarily a function of interstory drift (e.g. full-height drywall partitions) while for acceleration-sensitive components (e.g. mechanical equipment) damage is a function of the floor acceleration. Developing fragility curves for each possible nonstructural component is not practicable for the purposes of regional loss estimation and there is insufficient data to develop such fragility curves. Hence, in this methodology nonstructural building components are grouped into drift-sensitive and acceleration-sensitive component groups, and the damage functions estimated for each group are assumed to be "typical" of it subcomponents. Note, however, that damage depends on the anchorage/bracing provided to the nonstructural components. Damageability characteristics of each group are described by a set of fragility curves (see Subsection 5.4.3.3, HAZUS-MH MR3 Technical Manual 2006a).

The type of nonstructural components in a given building is a function of the building occupancy-use classification. For example, single-family residences would not have curtain wall panels, suspended ceilings, elevators, etc. while these items would be found in an office building. Hence, the relative values of nonstructural components in relation to the overall building replacement value vary with type of occupancy. In Chapter 15 (HAZUS-MH MR3 Technical Manual, 2006a), estimates of replacement cost breakdown between structural building components for different occupancy/use related classifications are provided; further breakdowns are provided by drift- and acceleration-sensitive nonstructural components.

In the following, general descriptions of the four nonstructural damage states are described for common nonstructural building components:

Partitions Walls

Slight Nonstructural Damage: A few cracks are observed at intersections of walls and ceilings and at corners of door openings.

Moderate Nonstructural Damage: Larger and more extensive cracks requiring repair and repainting; some partitions may require replacement of gypsum board or other finishes.

Extensive Nonstructural Damage: Most of the partitions are cracked and a significant portion may require replacement of finishes; some door frames in the partitions are also damaged and require re-setting.

Complete Nonstructural Damage: Most partition finish materials and framing may have to be removed and replaced; damaged studs repaired, and walls be refinished. Most door frames may also have to be repaired and replaced.

Suspended Ceilings

Slight Nonstructural Damage: A few ceiling tiles have moved or fallen down.
Moderate Nonstructural Damage: Falling of tiles is more extensive; in addition the ceiling support framing (T-bars) has disconnected and/or buckled at few locations; lenses have fallen off of some light fixtures and a few fixtures have fallen; localized repairs are necessary.
Extensive Nonstructural Damage: The ceiling system exhibits extensive buckling, disconnected t-bars and falling ceiling tiles; ceiling partially collapses at few locations and some light fixtures fall; repair typically involves removal of most or all ceiling tiles.
Complete Nonstructural Damage: The ceiling system is buckled throughout and/or fallen and requires complete replacement; many light fixtures fall.

Exterior Wall Panels

Slight Nonstructural Damage: Slight movement of the panels, requiring realignment.
Moderate Nonstructural Damage: The movements are more extensive; connections of panels to structural frame are damaged requiring further inspection and repairs; some window frames may need realignment
Extensive Nonstructural Damage: Most of the panels are cracked or otherwise damaged and misaligned, and most panel connections to the structural frame are damaged requiring thorough review and repairs; few panels fall or are in imminent danger of falling; some window panes are broken and some pieces of glass have fallen.
Complete Nonstructural Damage: Most panels are severely damaged, most connections are broken or severely damaged, some panels have fallen and most are in imminent danger of falling; extensive glass breakage and falling.

Electrical-Mechanical Equipment, Piping, Ducts

Slight Nonstructural Damage: The most vulnerable equipment (e.g. unanchored or on spring isolators) moves and damages attached piping or ducts.
Moderate Nonstructural Damage: Movements are larger and damage is more extensive; piping leaks at few locations; elevator machinery and rails may require realignment
Extensive Nonstructural Damage: Equipment on spring isolators topples and falls; other unanchored equipment slides or falls breaking connections to piping and ducts; leaks develop at many locations; anchored equipment indicate stretched bolts or strain at anchorages.
Complete Nonstructural Damage: Equipment is damaged by sliding, overturning or failure of their supports and is not operable; piping is leaking at many locations; some pipe and duct supports have failed causing pipes and ducts to fall or hang down; elevator rails are buckled or have broken supports and/or counterweights have derailed.

APPENDIX F: Building Replacement Cost Tables

Table F-1. Structural Repair Cost Ratios (in % of building replacement cost)

No.	Label	Occupancy Class	Structural Damage State			
			Slight	Moderate	Extensive	Complete
1	RES1	Single Family Dwelling	0.5	2.3	11.7	23.4
2	RES2	Mobile Home	0.4	2.4	7.3	24.4
3-8	RES3a-f	Multi Family Dwelling	0.3	1.4	6.9	13.8
9	RES4	Temporary Lodging	0.2	1.4	6.8	13.6
10	RES5	Institutional Dormitory	0.4	1.9	9.4	18.8
11	RES6	Nursing Home	0.4	1.8	9.2	18.4
12	COM1	Retail Trade	0.6	2.9	14.7	29.4
13	COM2	Wholesale Trade	0.6	3.2	16.2	32.4
14	COM3	Personal and Repair Services	0.3	1.6	8.1	16.2
15	COM4	Professional/Technical/ Business Services	0.4	1.9	9.6	19.2
16	COM5	Banks/Financial Institutions	0.3	1.4	6.9	13.8
17	COM6	Hospital	0.2	1.4	7	14
18	COM7	Medical Office/Clinic	0.3	1.4	7.2	14.4
19	COM8	Entertainment & Recreation	0.2	1	5	10
20	COM9	Theaters	0.3	1.2	6.1	12.2
21	COM10	Parking	1.3	6.1	30.4	60.9
22	IND1	Heavy	0.4	1.6	7.8	15.7
23	IND2	Light	0.4	1.6	7.8	15.7
24	IND3	Food/Drugs/Chemicals	0.4	1.6	7.8	15.7
25	IND4	Metals/Minerals Processing	0.4	1.6	7.8	15.7
26	IND5	High Technology	0.4	1.6	7.8	15.7
27	IND6	Construction	0.4	1.6	7.8	15.7
28	AGR1	Agriculture	0.8	4.6	23.1	46.2
29	REL1	Church/Membership Organization	0.3	2	9.9	19.8
30	GOV1	General Services	0.3	1.8	9	17.9
31	GOV2	Emergency Response	0.3	1.5	7.7	15.3
32	EDU1	Schools/Libraries	0.4	1.9	9.5	18.9
33	EDU2	Colleges/Universities	0.2	1.1	5.5	11

Table F-2. Acceleration Sensitive Non-structural Repair Cost Ratios (in % of building replacement cost)

No.	Label	Occupancy Class	Acceleration Sensitive Non-structural Damage State			
			Slight	Moderate	Extensive	Complete
1	RES1	Single Family Dwelling	0.5	2.7	8	26.6
2	RES2	Mobile Home	0.8	3.8	11.3	37.8
3-8	RES3a-f	Multi Family Dwelling	0.8	4.3	13.1	43.7
9	RES4	Temporary Lodging	0.9	4.3	13	43.2
10	RES5	Institutional Dormitory	0.8	4.1	12.4	41.2
11	RES6	Nursing Home	0.8	4.1	12.2	40.8
12	COM1	Retail Trade	0.8	4.4	12.9	43.1
13	COM2	Wholesale Trade	0.8	4.2	12.4	41.1
14	COM3	Personal and Repair Services	1	5	15	50
15	COM4	Professional/Technical/ Business Services	0.9	4.8	14.4	47.9
16	COM5	Banks/Financial Institutions	1	5.2	15.5	51.7
17	COM6	Hospital	1	5.1	15.4	51.3
18	COM7	Medical Office/Clinic	1	5.2	15.3	51.2
19	COM8	Entertainment & Recreation	1.1	5.4	16.3	54.4
20	COM9	Theaters	1	5.3	15.8	52.7
21	COM10	Parking	0.3	2.2	6.5	21.7
22	IND1	Heavy	1.4	7.2	21.8	72.5
23	IND2	Light	1.4	7.2	21.8	72.5
24	IND3	Food/Drugs/Chemicals	1.4	7.2	21.8	72.5
25	IND4	Metals/Minerals Processing	1.4	7.2	21.8	72.5
26	IND5	High Technology	1.4	7.2	21.8	72.5
27	IND6	Construction	1.4	7.2	21.8	72.5
28	AGR1	Agriculture	0.8	4.6	13.8	46.1
29	REL1	Church/Membership Organization	0.9	4.7	14.3	47.6
30	GOV1	General Services	1	4.9	14.8	49.3
31	GOV2	Emergency Response	1	5.1	15.1	50.5
32	EDU1	Schools/Libraries	0.7	3.2	9.7	32.4
33	EDU2	Colleges/Universities	0.6	2.9	8.7	29

Table F-3. Drift Sensitive Non-structural Repair Costs (in % of building replacement cost)

No.	Label	Occupancy Class	Drift Sensitive Non-structural Damage State			
			Slight	Moderate	Extensive	Complete
1	RES1	Single Family Dwelling	1	5	25	50
2	RES2	Mobile Home	0.8	3.8	18.9	37.8
3-8	RES3a-f	Multi Family Dwelling	0.9	4.3	21.3	42.5
9	RES4	Temporary Lodging	0.9	4.3	21.6	43.2
10	RES5	Institutional Dormitory	0.8	4	20	40
11	RES6	Nursing Home	0.8	4.1	20.4	40.8
12	COM1	Retail Trade	0.6	2.7	13.8	27.5
13	COM2	Wholesale Trade	0.6	2.6	13.2	26.5
14	COM3	Personal and Repair Services	0.7	3.4	16.9	33.8
15	COM4	Professional/Technical/ Business Services	0.7	3.3	16.4	32.9
16	COM5	Banks/Financial Institutions	0.7	3.4	17.2	34.5
17	COM6	Hospital	0.8	3.5	17.4	34.7
18	COM7	Medical Office/Clinic	0.7	3.4	17.2	34.4
19	COM8	Entertainment & Recreation	0.7	3.6	17.8	35.6
20	COM9	Theaters	0.7	3.5	17.6	35.1
21	COM10	Parking	0.4	1.7	8.7	17.4
22	IND1	Heavy	0.2	1.2	5.9	11.8
23	IND2	Light	0.2	1.2	5.9	11.8
24	IND3	Food/Drugs/Chemicals	0.2	1.2	5.9	11.8
25	IND4	Metals/Minerals Processing	0.2	1.2	5.9	11.8
26	IND5	High Technology	0.2	1.2	5.9	11.8
27	IND6	Construction	0.2	1.2	5.9	11.8
28	AGR1	Agriculture	0	0.8	3.8	7.7
29	REL1	Church/Membership Organization	0.8	3.3	16.3	32.6
30	GOV1	General Services	0.7	3.3	16.4	32.8
31	GOV2	Emergency Response	0.7	3.4	17.1	34.2
32	EDU1	Schools/Libraries	0.9	4.9	24.3	48.7
33	EDU2	Colleges/Universities	1.2	6	30	60